

# Search for Fully Leptonic B Decays

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## at Babar

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*The Ohio State University*

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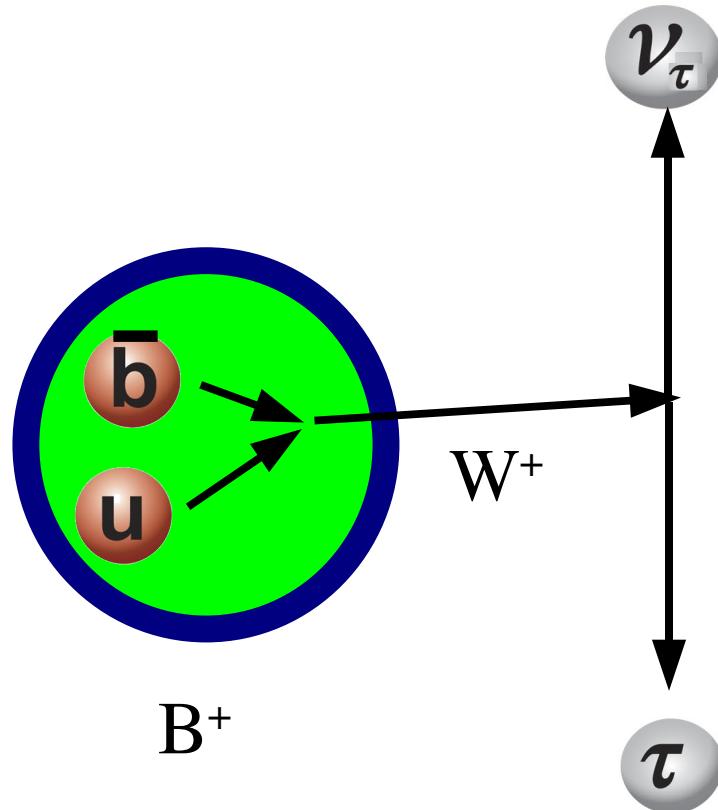
# Outline

- ◆ Motivation
- ◆ Standard Model Predictions & New physics
- ◆ Experimental Procedure
- ◆ Systematics
- ◆ Numerical Results
- ◆ Branching fraction and upper limit
- ◆ Future Outlook



# What are we looking for & why?

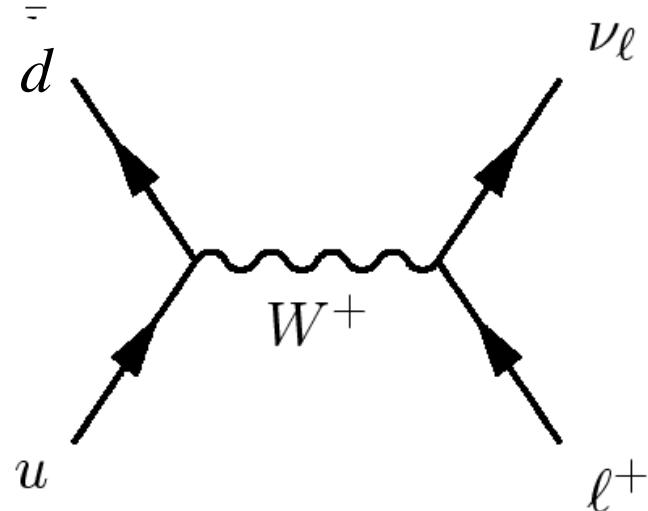
$$B^+ \rightarrow \ell^+ \nu_\ell (\ell = e, \mu, \tau)$$



- ♦ Rare Decays
- ♦ Test of Standard Model
- ♦ Measure wave function overlap of quarks
- ♦ Weak Interaction Probe
- ♦ New physics could contribute as well



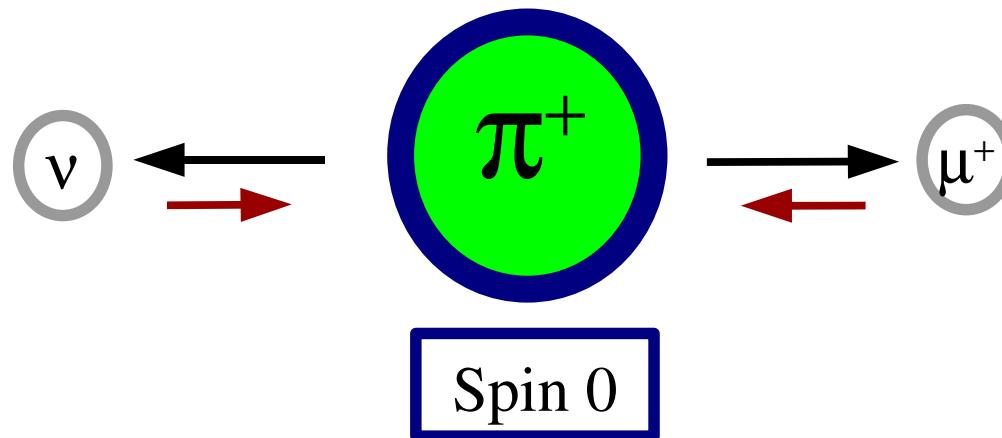
# Already know a familiar decay



$$\mathcal{B}(\pi^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 m_\pi}{8\pi} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_\pi^2}\right)^2 f_\pi^2 \tau_\pi$$

$$\text{Helicity} = \vec{p} \cdot \vec{S}$$

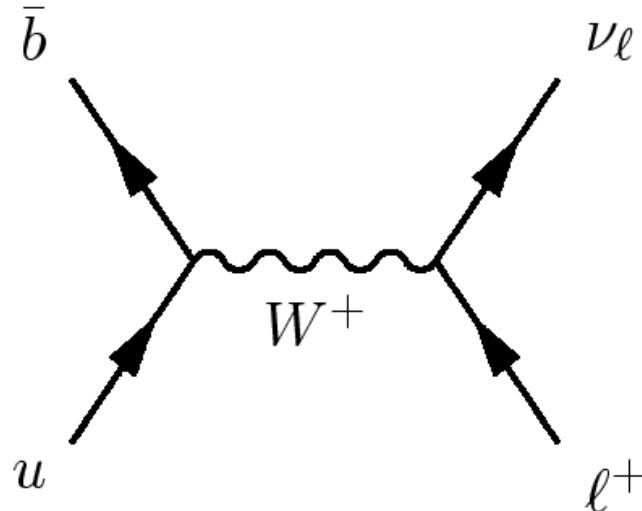
Weak force  
couples to  
negative  
helicity  $\nu$



Must be  
negative  
helicity,  
easier with  
more mass



# Analogous to our target



$$\mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

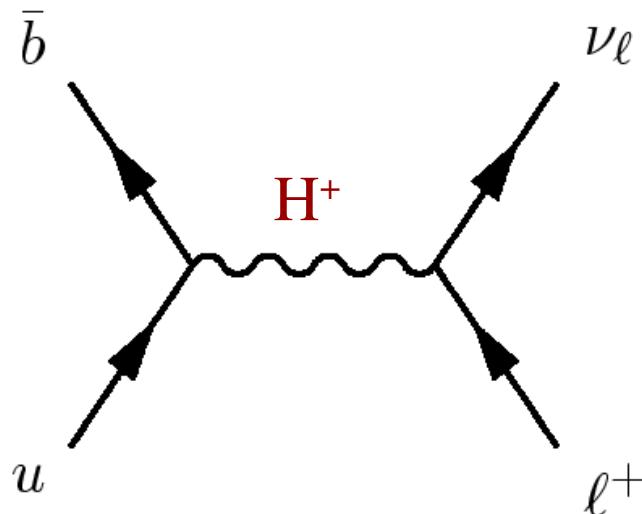
Calculate from branching fraction

- ◆ Helicity suppresses the BFs of the light leptons
- ◆ SM Prediction
  - ◆  $|V_{ub}| = (3.96 \pm 0.15^{+0.20}_{-0.23}) \times 10^{-3}$  (HFAG)
  - ◆  $f_B = 0.216 \pm 0.022$  GeV (Lattice QCD)

		$B^+ \rightarrow e^+ \nu_e$	$B^+ \rightarrow \mu^+ \nu_\mu$	$B^+ \rightarrow \tau^+ \nu_\tau$
Prediction	SM	$(1.4 \pm 0.3) \times 10^{-11}$	$(5.8 \pm 1.3) \times 10^{-7}$	$(1.3 \pm 0.3) \times 10^{-4}$
PDG Values		$< 9.8 \times 10^{-7}$	$< 1.7 \times 10^{-6}$	$(1.4 \pm 0.4) \times 10^{-4}$



# Potential New Physics



Charged Higgs boson,  
from the Two-Higgs  
Doublet Model (2HDM)  
can modify BF

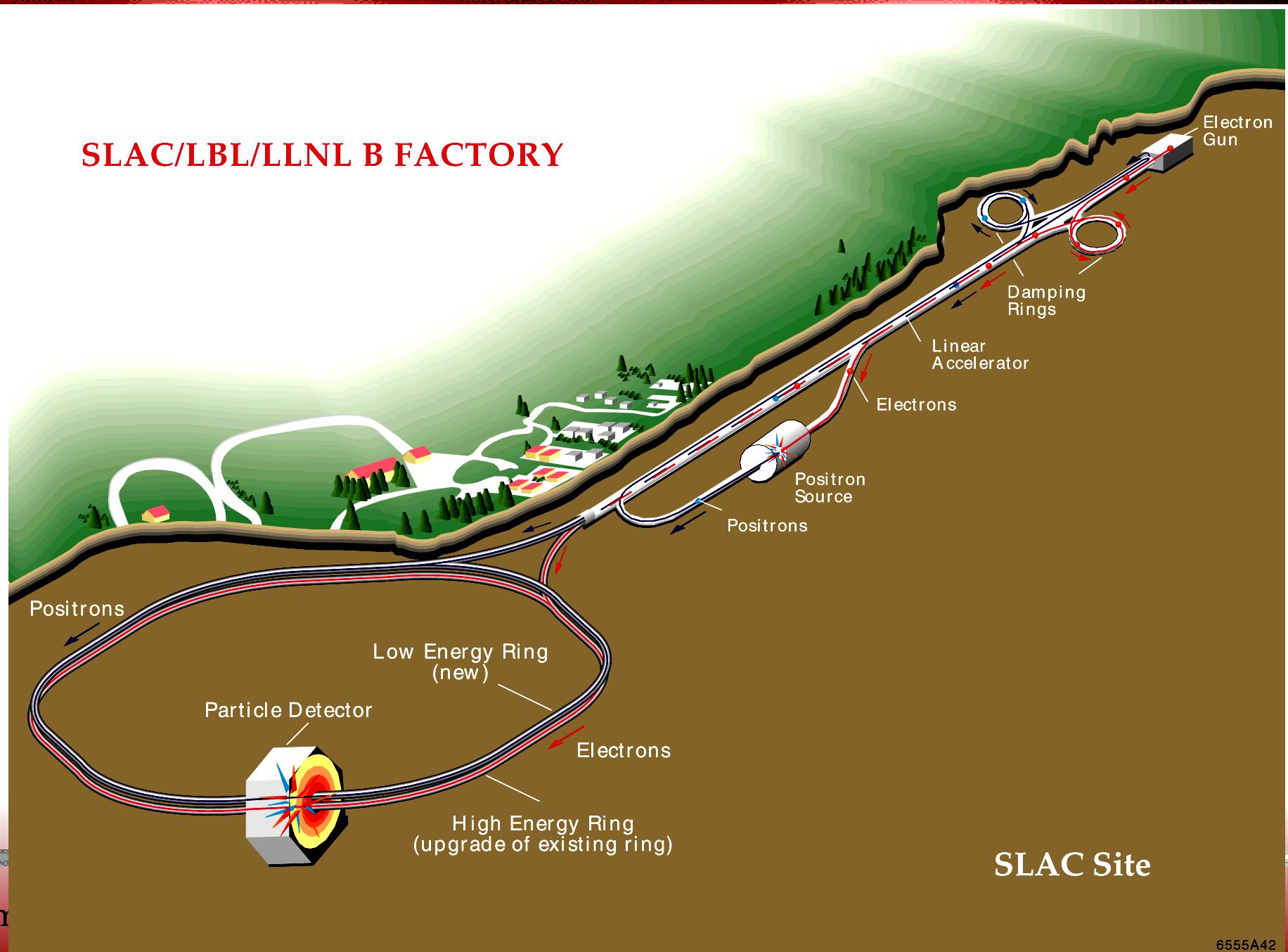
$$\mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell) = \mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell)_{SM} \times \left| 1 - \tan^2 \beta \frac{\frac{m_{B^+}^2}{m_{H^+}^2}}{} \right|^2$$

The ratio of VEVs  
for the u and d type  
Higgs bosons

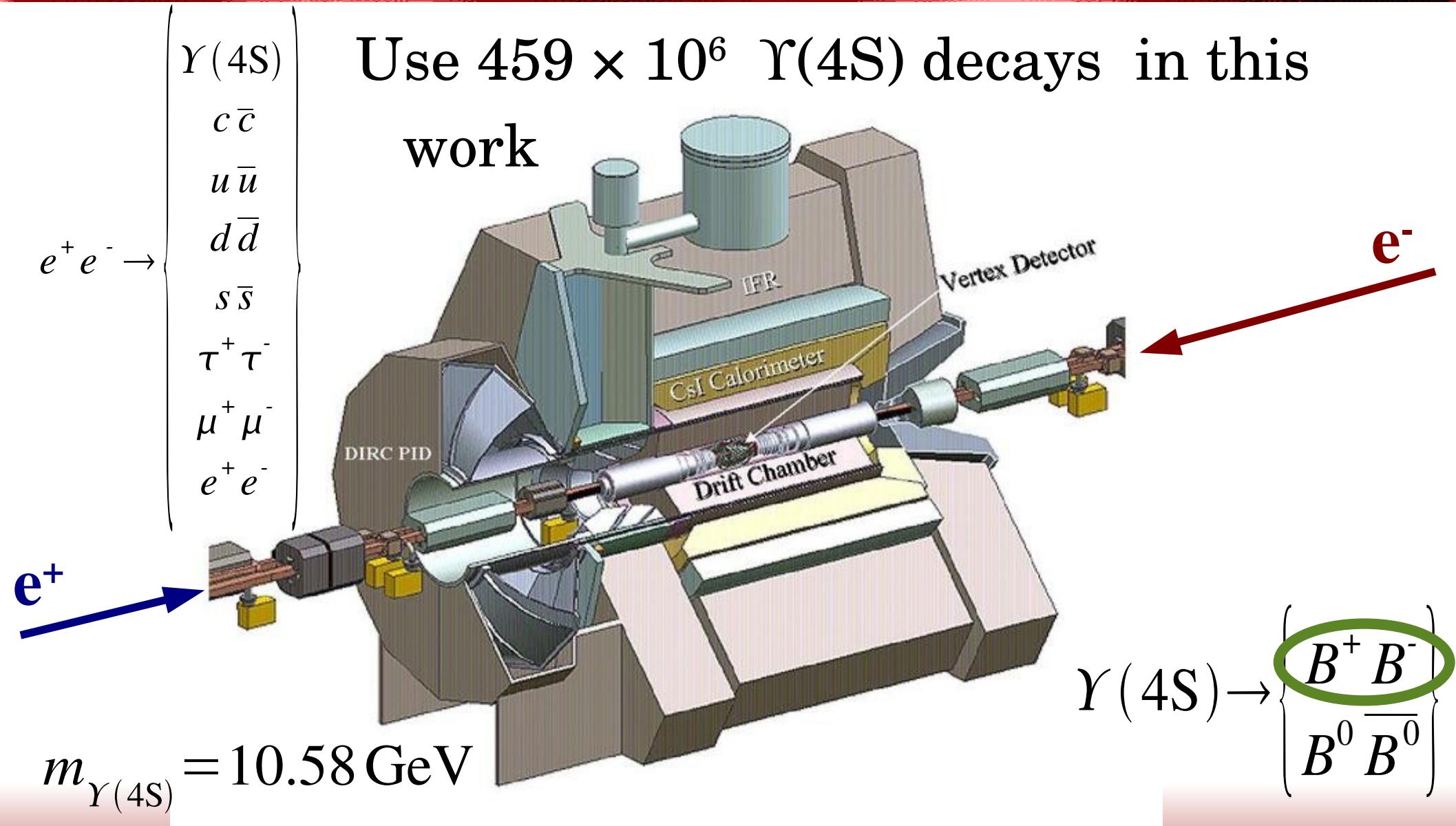
Charged  
Higgs  
Mass



# Stanford Linear Accelerator Center

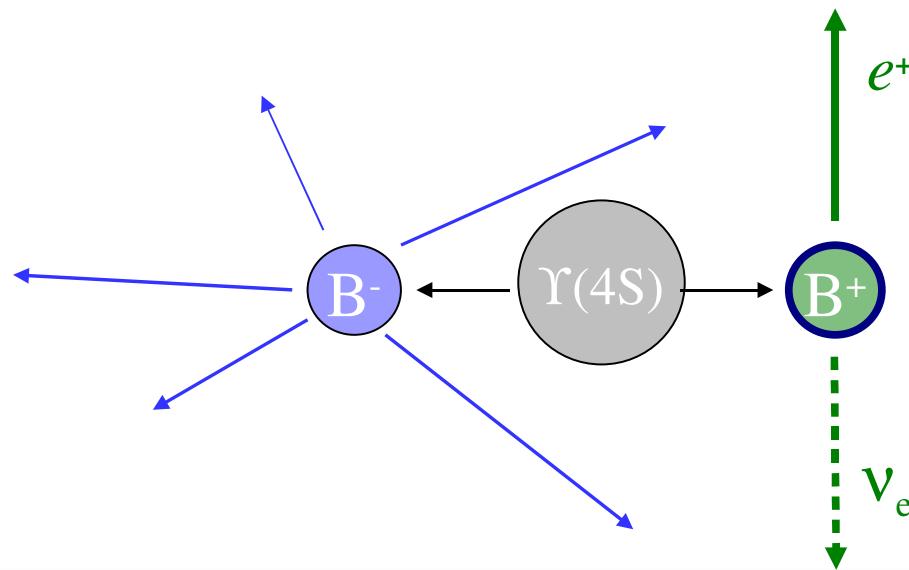


# BaBar



# Reasons for Tag

- ◆ Problem: Neutrinos undetectable
- ◆ Solution: Reduce the number of unknowns by reconstructing one “tag”  $B$  in a well understood set of decay channels



# Semileptonic Tag Reconstruction

Tag  $B^- \rightarrow D^0 \ell^- \bar{\nu}_\ell X$  ( $\ell = e$  or  $\mu$ )

$$D^0 \rightarrow K^- \pi^+$$

$$D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$$

$$D^0 \rightarrow K^- \pi^+ \pi^0$$

$$D^0 \rightarrow K_S^0 \pi^- \pi^+ (K_S^0 \rightarrow \pi^+ \pi^-)$$

$$\mathcal{B}(B^- \rightarrow D^0 \ell^- \bar{\nu}_\ell X) \approx 20\%$$

*First search for  
 $B \rightarrow \mu\nu$ ,  $B \rightarrow e\nu$   
using this tag*

- ◆ Pioneered by Babar
- ◆ Reconstruct tag side assuming  $\nu$  is only missing particle
- ◆  $X = \text{nothing}, \gamma$  or  $\pi^0$  from higher mass charm state
- ◆ This yields lower purity
- ◆ Higher efficiency
  - ◆  $\sim 1\%$  vs.  $\sim 0.2\%$



# Complementary Methods

- ♦ No tags (Inclusive), not applicable to  $B \rightarrow \tau v$ 
  - ◆ Find highest momentum lepton, make a  $B$  with the rest of the event. High background, best limits
- ♦ Hadronic tags
  - ◆ Reconstruct Tag  $B$  using fully hadronic modes
  - ◆ Fully reconstruct tag  $B$
  - ◆ Branching Fraction  $\approx 10\%$
- ♦ Double statistical power in combination



# Measurements thus far

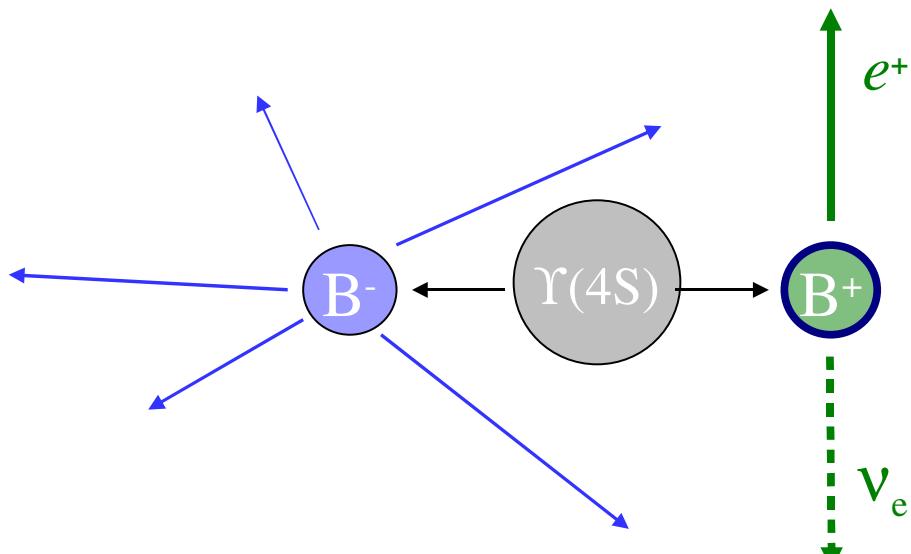
		$B^+ \rightarrow e^+ \nu_e$	$B^+ \rightarrow \mu^+ \nu_\mu$	$B^+ \rightarrow \tau^+ \nu_\tau$
PDG Values [1]		$< 9.8 \times 10^{-7}$	$< 1.7 \times 10^{-6}$	$(1.4 \pm 0.4) \times 10^{-4}$
Inclusive Meas.	<i>BABAR</i> [9]	-	$< 1.3 \times 10^{-6}$	N/A
	<i>Belle</i> [10]	$< 9.8 \times 10^{-7}$	$< 1.7 \times 10^{-6}$	N/A
Hadronic Tag Meas.	<i>BABAR</i>	$< 5.2 \times 10^{-6}$ [11]	$< 5.6 \times 10^{-6}$ [11]	$(1.8_{-0.9}^{+1.0}) \times 10^{-4}$ [12]
	<i>Belle</i>	-	-	$(1.8 \pm 0.7) \times 10^{-4}$ [13]
Semilep. Tag Meas.	<i>BABAR</i>	This Talk	This Talk	This Talk
	<i>Belle</i> [14]	-	-	$(1.65_{-0.37-0.37}^{+0.38+0.35}) \times 10^{-4}$

[9] arXiv:0807.4187 [10] *Phys. Lett.* **B647**:67-73 [11] arXiv:0801.0697

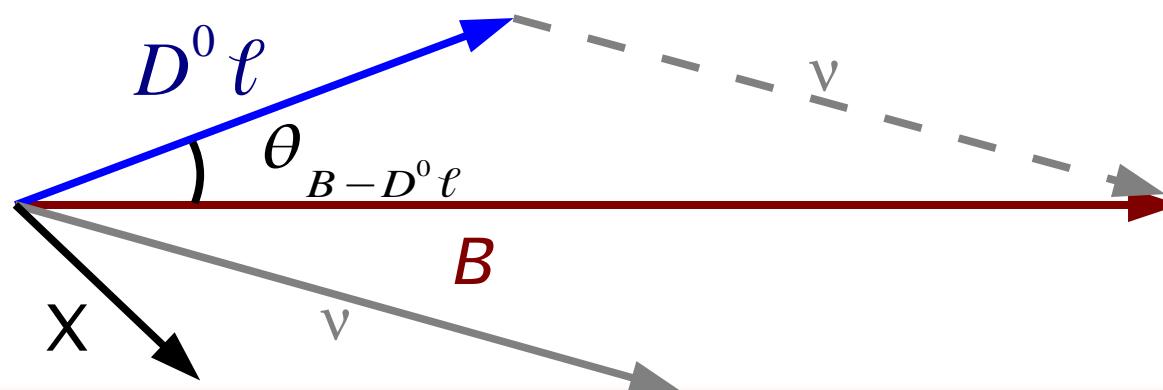
[12] *Phys. Rev.* **D77**:011107 [13] *Phys Rev. Lett.* **97**:251802 [14] arXiv:0809.3834



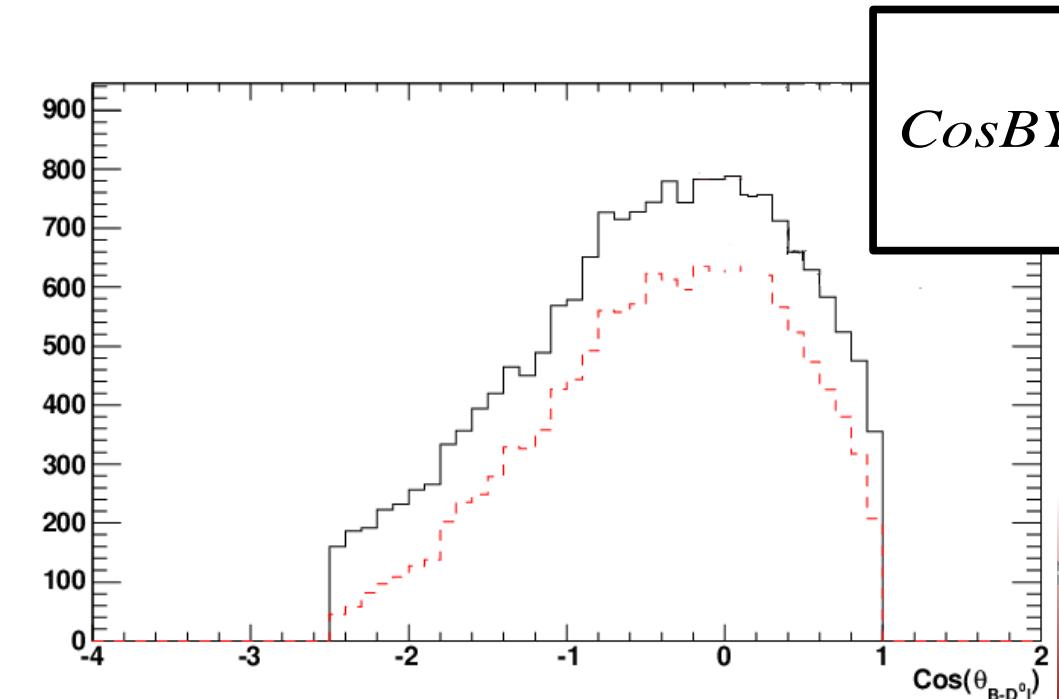
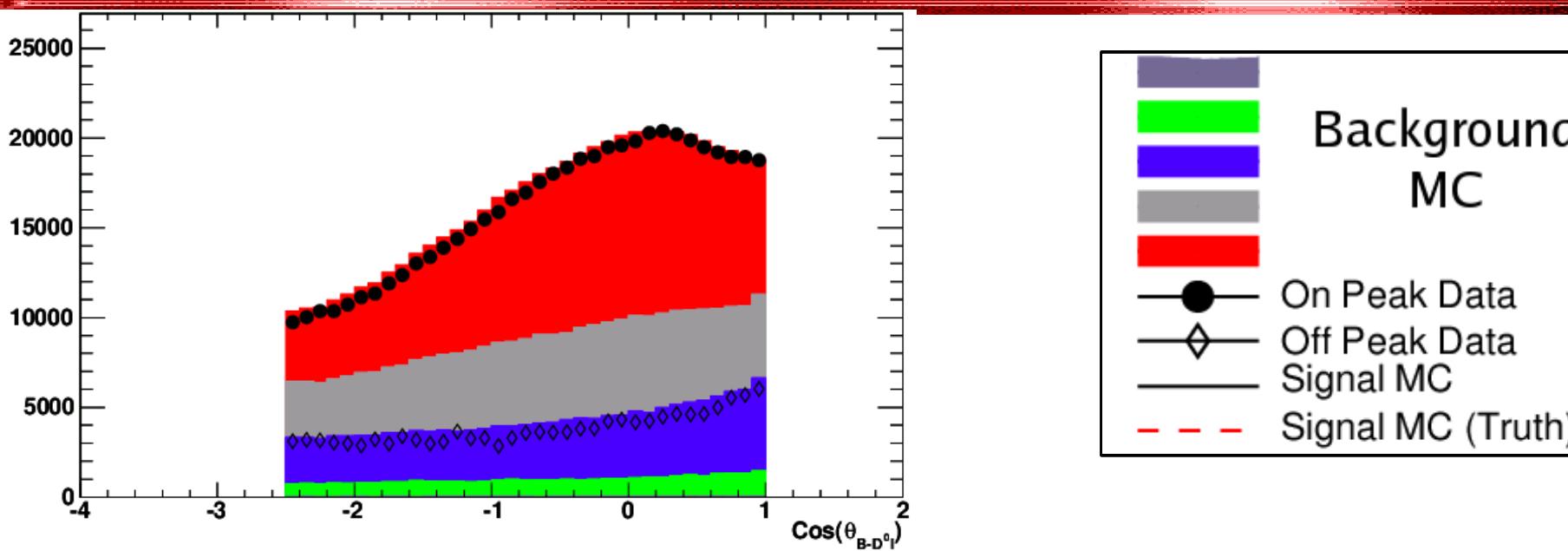
# Tag B Kinematics: CosBY



- Tag  $\nu$  prevents meas. CM frame
- Use beam info to calculate angle between  $B$  and  $D^0 l$



# Tag B Kinematics: CosBY



$$\text{CosBY} \equiv \cos(\theta_{B-D^0\ell}) = \frac{2 E_B E_{D^0\ell} - m_B^2 - m_{D^0\ell}^2}{2 |\vec{p}_B| |\vec{p}_{D^0\ell}|}$$

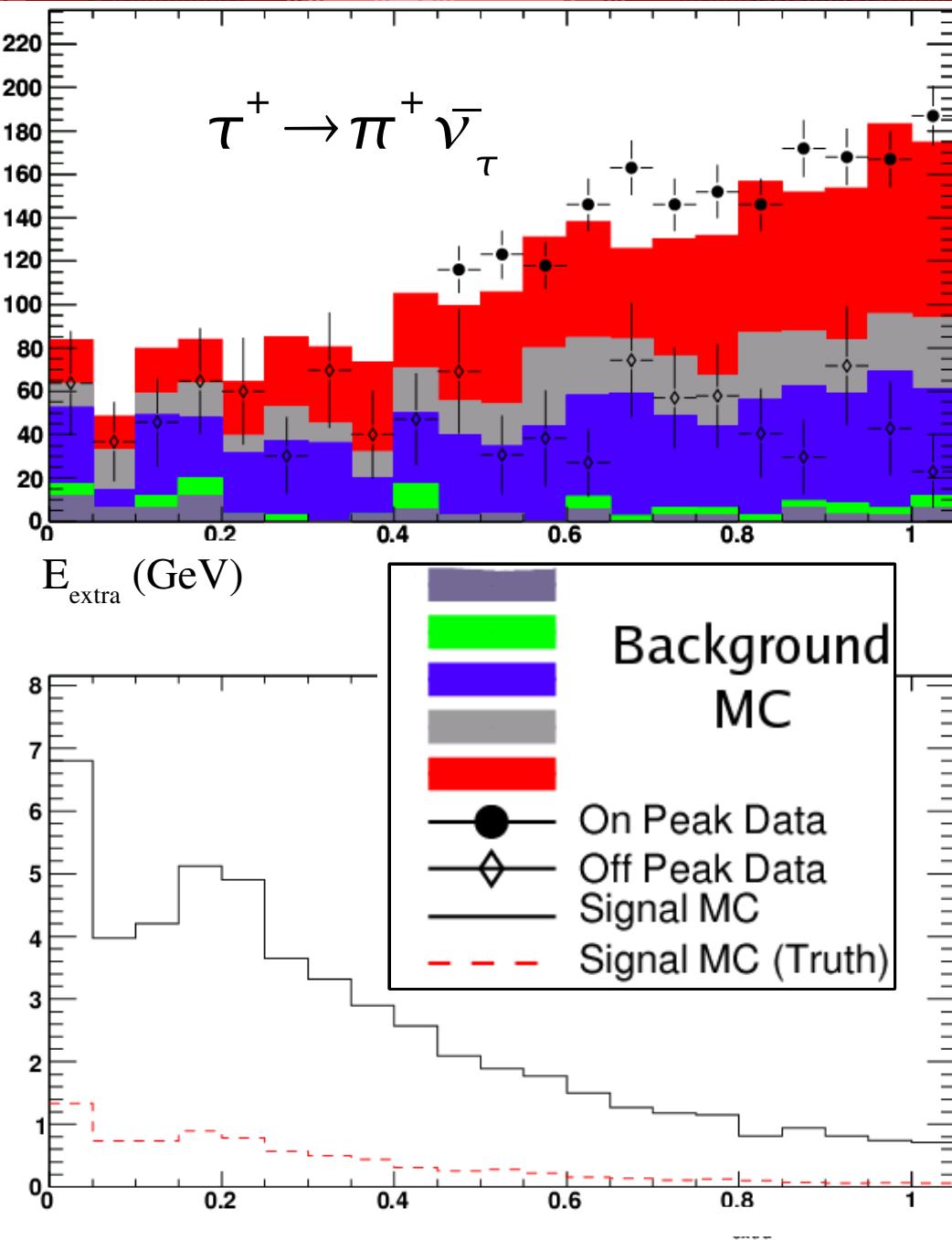
Presence of X causes  
values < -1

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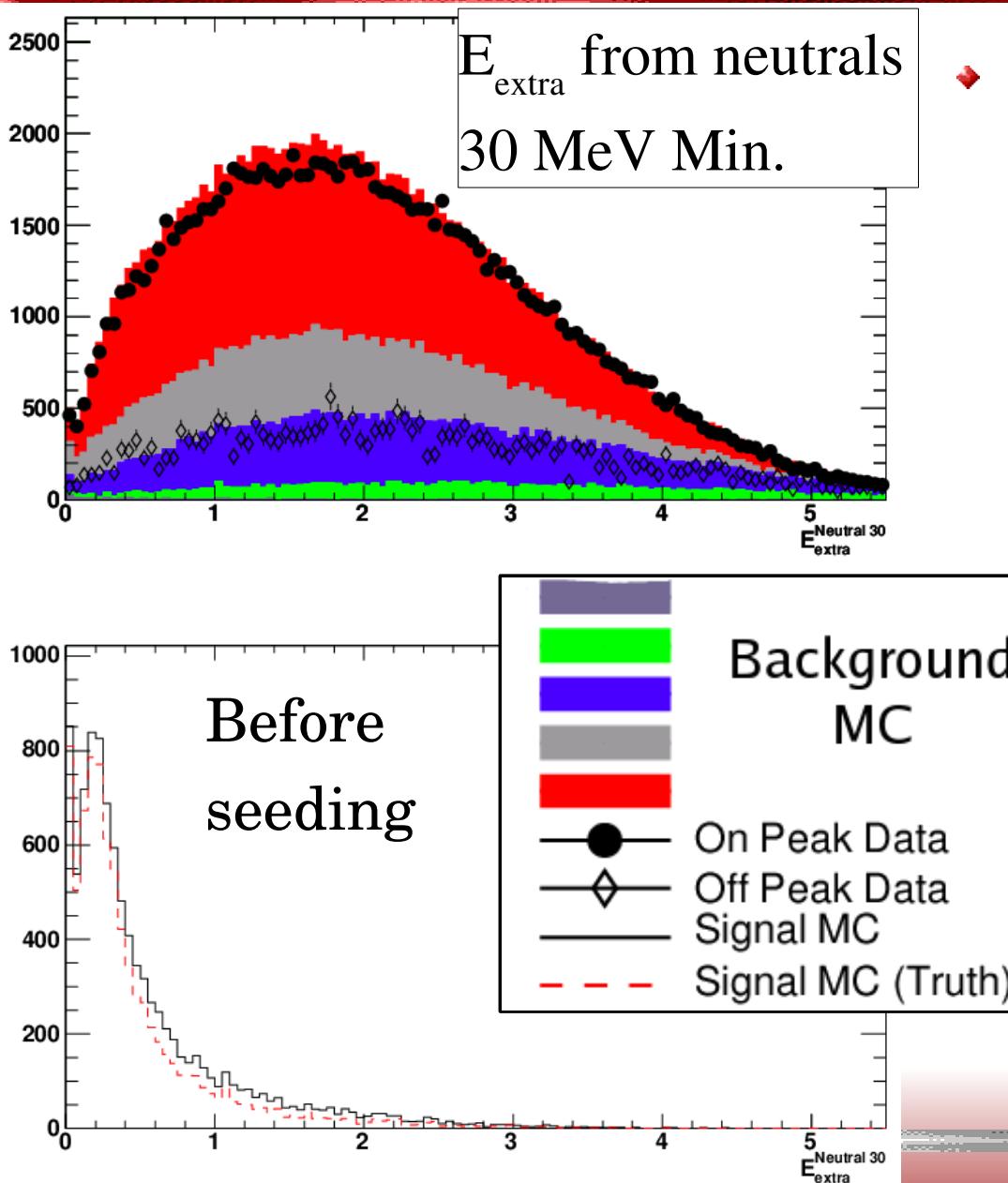
# Tag B Kinematics: $E_{\text{extra}}$



- $E_{\text{extra}} = \text{all energy after both } B\text{'s are reconstructed.}$
- Should be zero for an ideal, fully reconstructed, event.
- “Blind” signal region until analysis selection is complete



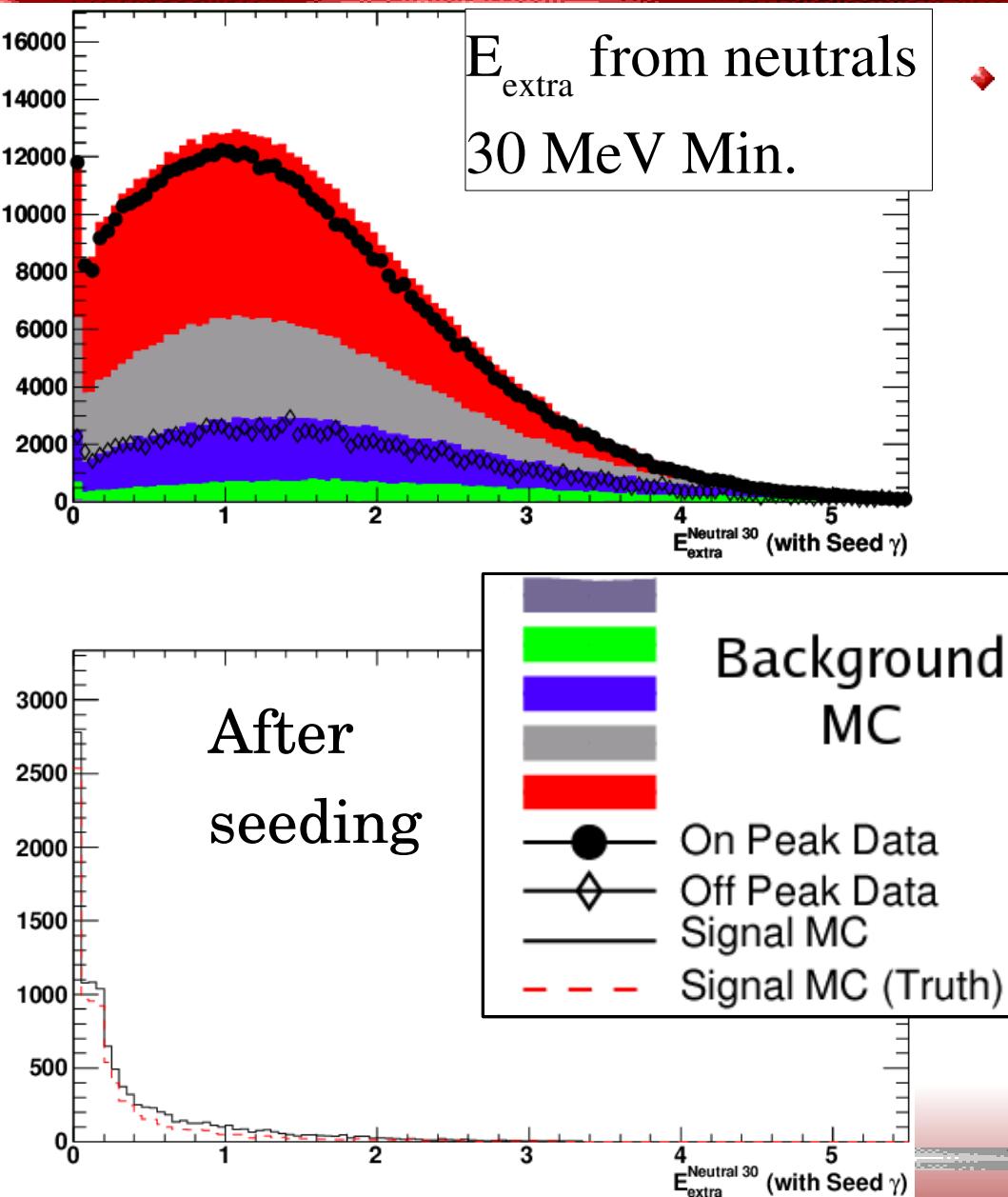
# Seeding Method



- Remove a “seed”  $\gamma$  from other variables and combine with the tag  $D^0$ 
  - $E_\gamma^* < 300 \text{ MeV}$
- Recalculate relevant variables.
- If the new CosBY is closer to 1, keep new configuration.



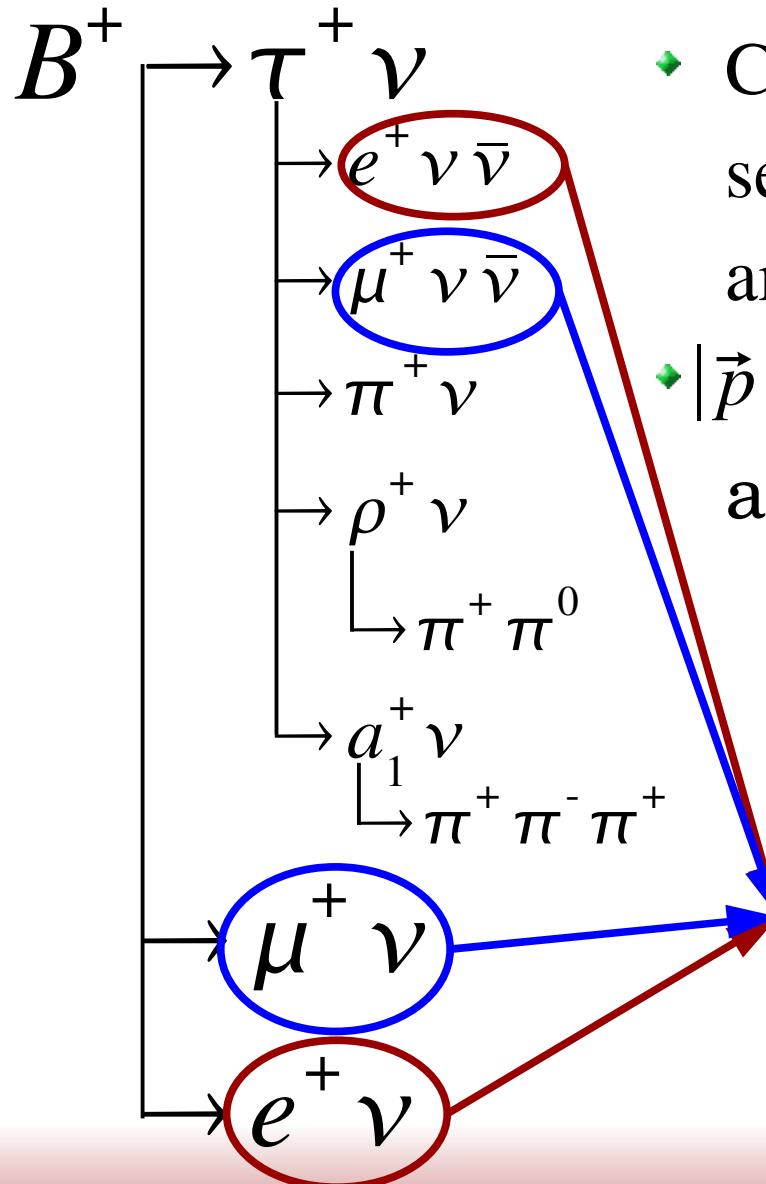
# Seeding Comparison



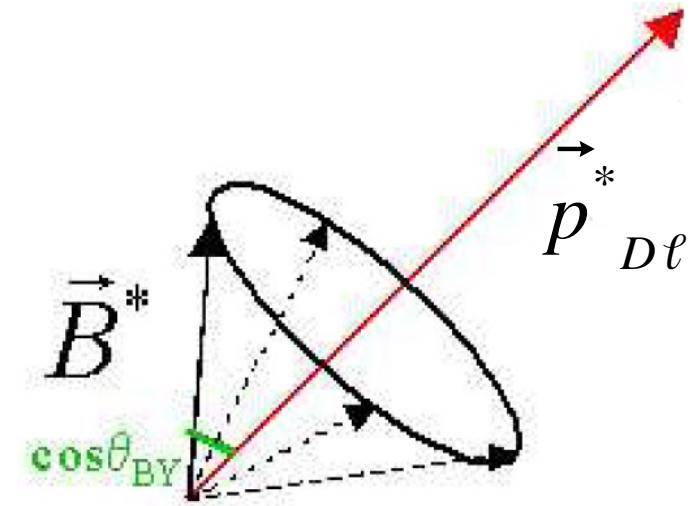
- Remove a “seed”  $\gamma$  from other variables and combine with the tag  $D^0$
- $E_{\gamma}^* < 300 \text{ MeV}$
- Recalculate relevant variables.
- If the new CosBY is closer to 1, keep new configuration.



# Signal Side Reconstruction



- Calculate  $|\vec{p}_\ell|$  at several points around BY cone
- $|\vec{p}'_\ell| = \text{average of all results}$



Use  $|\vec{p}'_\ell|$  for separation

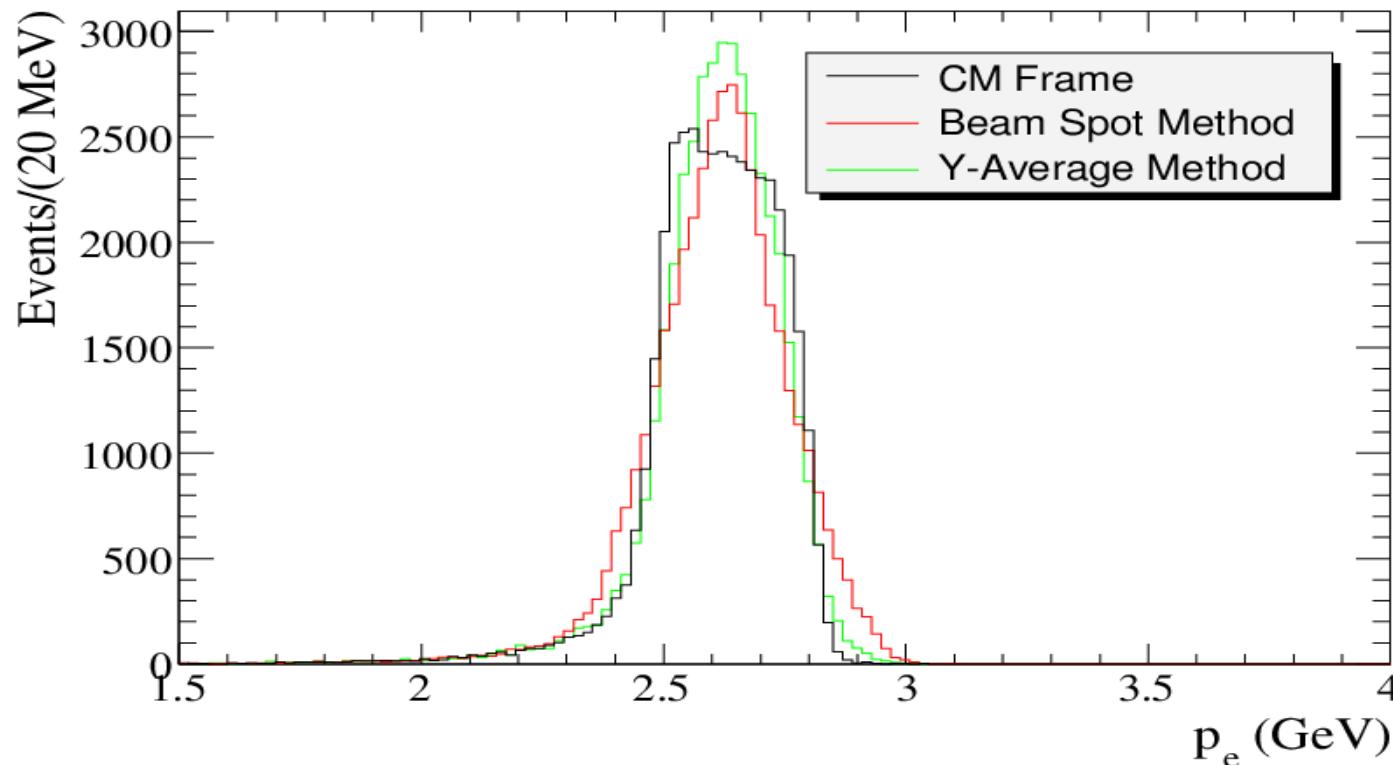
$$\text{Two body } \Rightarrow |\vec{p}'_\ell| \approx \frac{m_B}{2} = 2.64 \text{ GeV}$$

$$|\vec{p}'_e| \leq 2.25 \text{ GeV} \Rightarrow \tau^+ \rightarrow e^+ \nu \bar{\nu}$$

$$|\vec{p}'_\mu| \leq 2.30 \text{ GeV} \Rightarrow \tau^+ \rightarrow \mu^+ \nu \bar{\nu}$$



# Example: $B^+ \rightarrow e^+ \nu_e$



Tau decays in flight, daughters smear spectrum

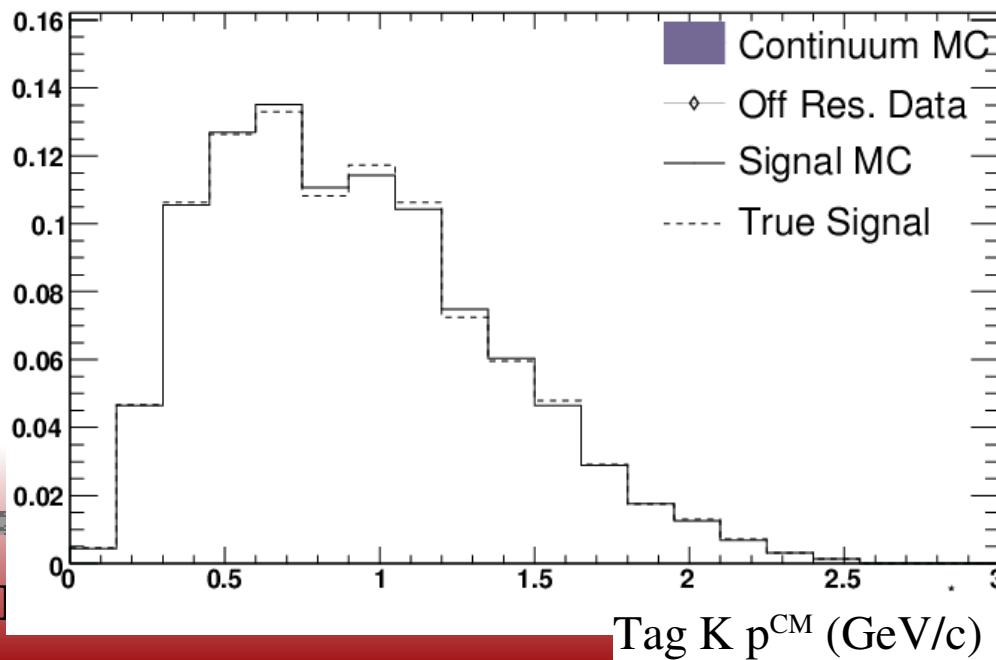
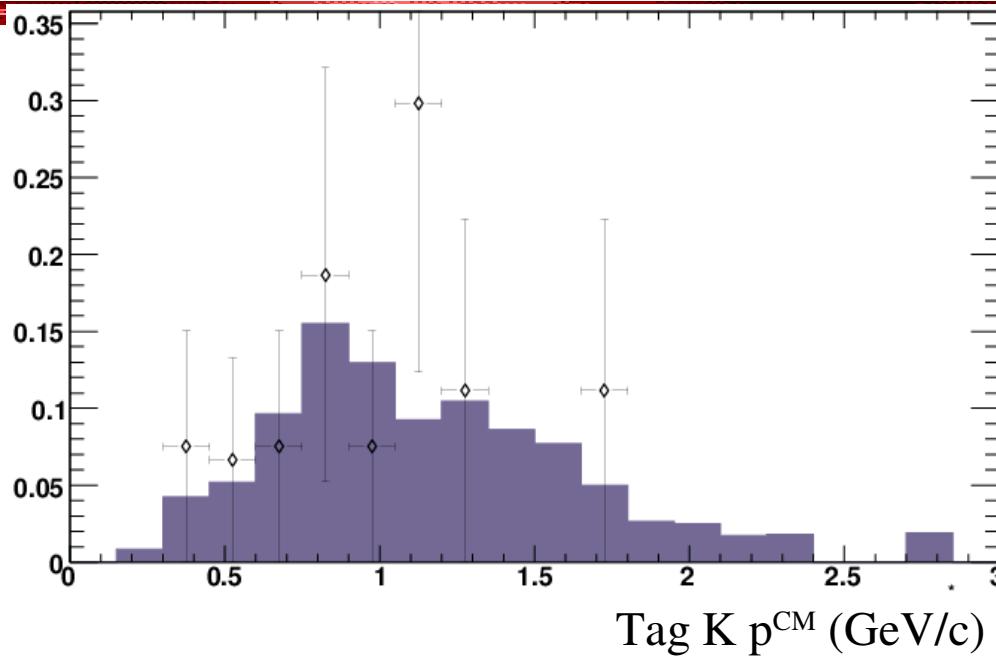


# Signal Variables

- ◆ Cannot reconstruct B mass, so we use...
  - ◆  $E_{\text{extra}} = \text{all energy after both } B\text{'s are reconstructed.}$
  - ◆ Momentum of signal lepton in  $B$  rest frame ( $p'_l$ )
- ◆ Remaining variables considered for likelihood ratios (LHRs) composed of probability density functions (PDFs).
  - ◆ Separate LHRs for continuum and  $B\bar{B}$  background and for each of the 7 signal modes



# PDFs for LHRs



- Made after tag cuts
- Normalize histograms of cont. and signal MC to unit area.
- Call height of hist. bin  $P_s(x)$  for signal MC and  $P_b(x)$  for BG MC

$$P(x) = \frac{P_s(x)}{P_s(x) + P_b(x)}$$



# Selecting PDFs for the LHRs

- ♦ We have a large number of PDFs (up to 27)
  - ♦ Remove those that are not helpful in the LHRs
- ♦ Remove each PDF to see effect on figure of merit (FOM)
- ♦ Calculate variation from all PDFs included
- ♦ Eliminate PDF if it degrades performance
- ♦ Eliminate if physics tells us it should not help (e.g. Tag side variables in BB MC).



# Cut Optimization

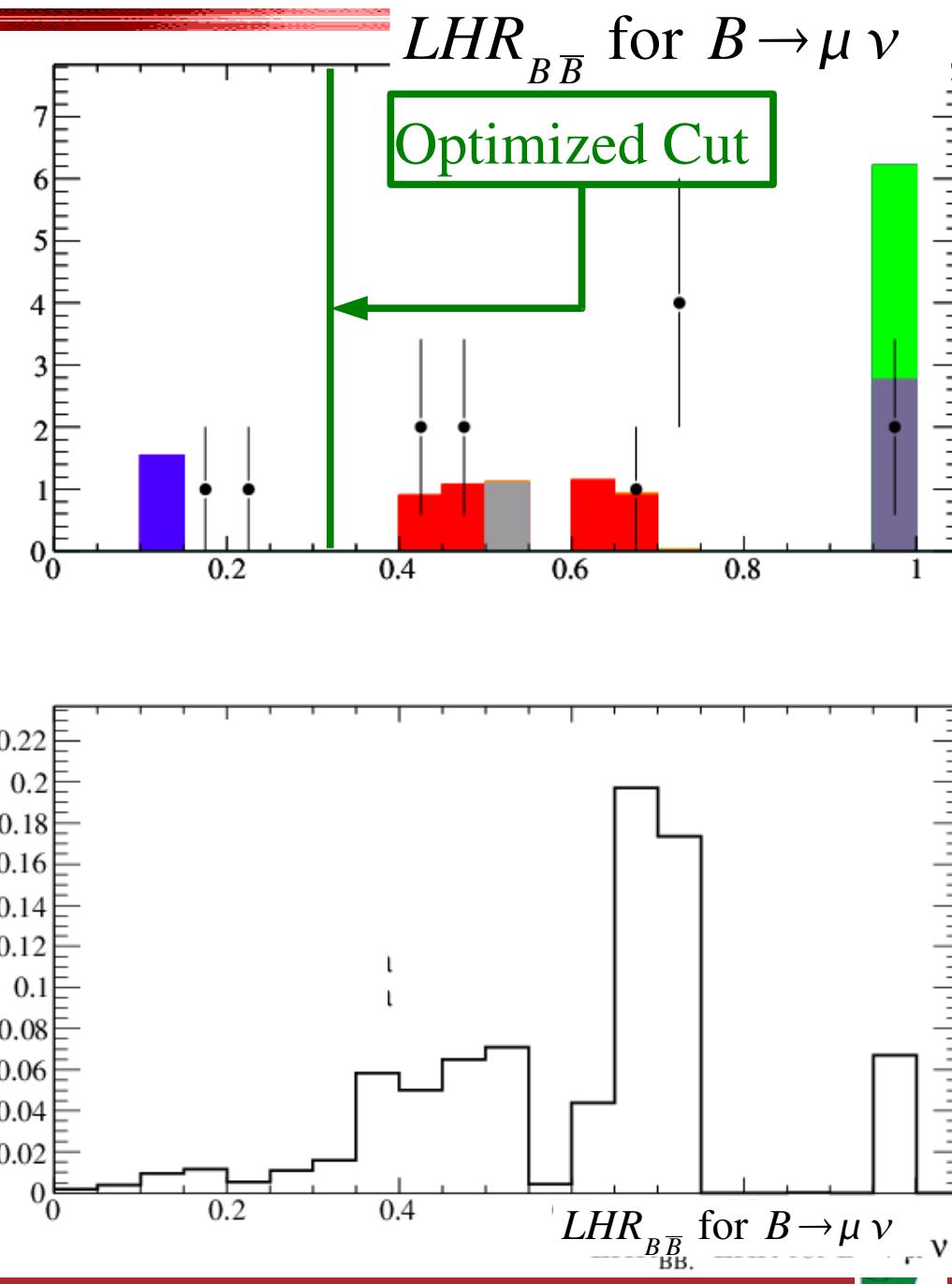
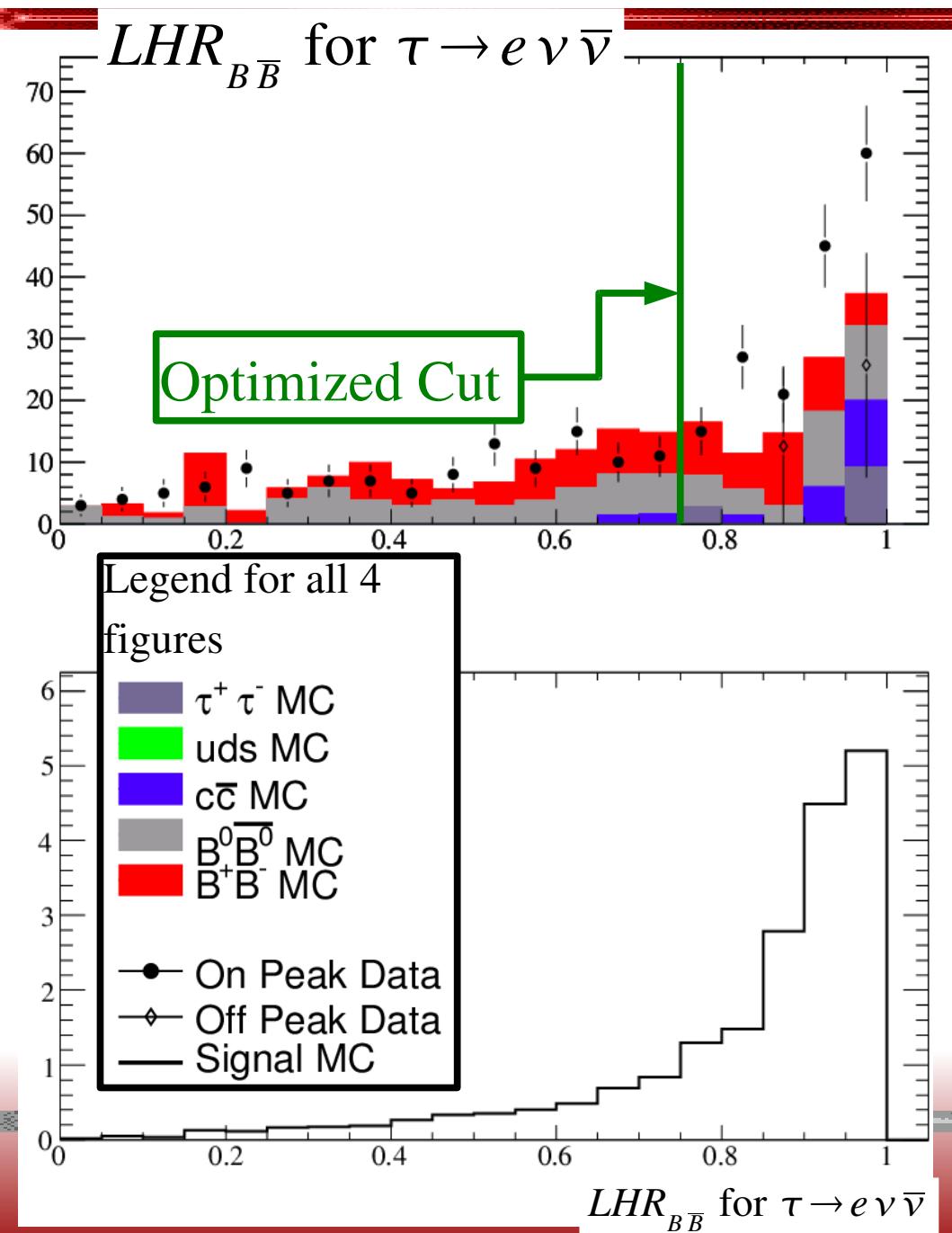
- Maximize Significance for  $B \rightarrow \tau\nu$
- Maximize Punzi FOM for  $B \rightarrow e\nu$  and  $B \rightarrow \mu\nu$

$$\text{Significance} = \frac{N_{sig}}{\sqrt{N_{sig} + N_{BG}}}$$

$$\text{Punzi} = \frac{N_{sig}}{\frac{N_{\sigma}}{2} + \sqrt{N_{BG}}} \quad N_{\sigma} = 3$$

Mode	$E_{\text{extra}}$	$LHR_{B\bar{B}}$	$LHR_{\text{cont.}}$	$p'_{\text{sig } \ell}$
$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	[0,0.24] GeV	[0.74,1]	[0.16,1]	[0.00,2.25] GeV
$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	[0,0.24] GeV	[0.14,1]	[0.72,1]	[0.00,2.30] GeV
$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	[0,0.35] GeV	[0.57,1]	[0.8,1]	-
$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	[0,0.24] GeV	[0.97,1]	[0.95,1]	-
$\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$	[0,0.31] GeV	[0.97,1]	[0.93,1]	-
$B^+ \rightarrow \mu^+ \nu_\mu$	[0,0.72] GeV	[0.33,1]	[0.75,1]	[2.45,2.92] GeV
$B^+ \rightarrow e^+ \nu_e$	[0,0.57] GeV	[0.00,1]	[0.01,1]	[2.52,3.02] GeV

# LHR Examples

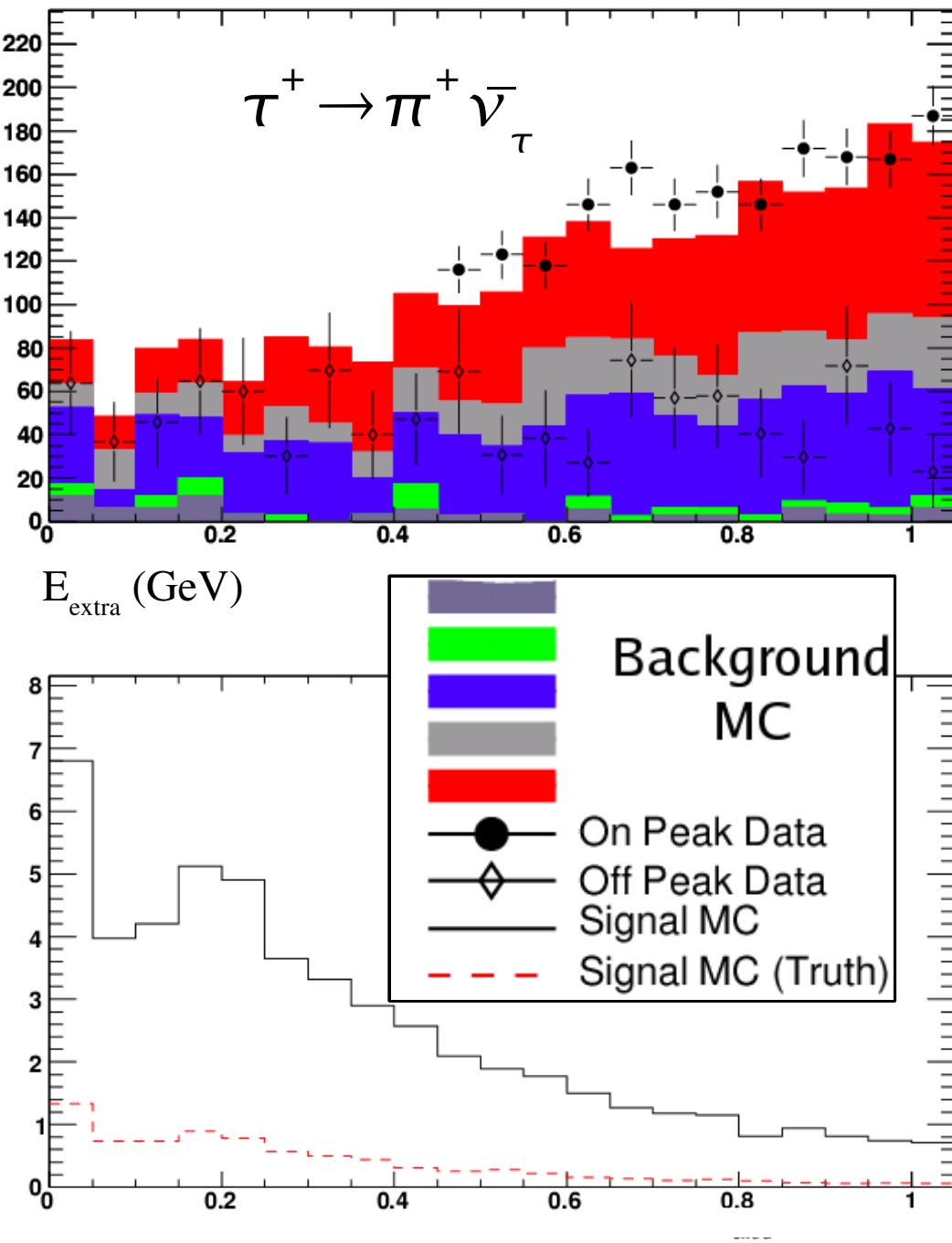


# Signal & Background Predictions

- ♦ Need BG prediction to tell if we see signal
- ♦ Do not want to us MC alone
- ♦ Have several sidebands in data from final selection variables
  - ♦  $E_{\text{extra}}$ ,  $\text{LHR}_{\text{BB}}$ ,  $\text{LHR}_{\text{cont}}$ ,  $p'_{\text{sig } l}$ ,  $D^0$  Mass
- ♦ Choose one for prediction and cross-check with the others.



# Signal & Background Predictions



Ratio of Sideband to  
Signal Region in MC  
( $R^{\text{MC}}$ )

$$N_{\text{exp,Sig}} = N_{\text{data,SideB}} \cdot R^{\text{MC}}$$

$$R^{\text{MC}} = \frac{N_{\text{MC,Sig}}}{N_{\text{MC,SideB}}}$$

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# Signal & Background Predictions

- ◆ Use  $E_{\text{extra}}$  for prediction
  - ◆ SB defined as  $E_{\text{extra}} > 0.72 \text{ GeV}$  ( $B \rightarrow \mu\nu$ )
  - ◆  $E_{\text{extra}} > 0.6 \text{ GeV}$  (all other modes)
  - ◆ Validate with remaining sidebands and MC
- ◆ Signal prediction from signal MC sample

## Signal Predictions Assuming

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = 1.0 \times 10^{-4}$$

$$\mathcal{B}(B^+ \rightarrow \mu^+ \nu) = 5.0 \times 10^{-7}$$

$$\mathcal{B}(B^+ \rightarrow e^+ \nu) = 1.0 \times 10^{-11}$$

Mode	Signal Prediction
$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	$15.14 \pm 0.33$
$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	$12.09 \pm 0.29$
$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	$18.96 \pm 0.37$
$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	$6.56 \pm 0.22$
$B^+ \rightarrow \tau^+ \nu_\tau$	$53.03 \pm 0.63$
$B^+ \rightarrow \mu^+ \nu_\mu$	$0.74 \pm 0.01$
$B^+ \rightarrow e^+ \nu_e$	$(1.84 \pm 0.02) \times 10^{-5}$



# Background Predictions

Mode	MC Counting	$D^0$ Mass	$E_{\text{extra}}$	$LHR_{\text{cont.}}$	$LHR_{B\bar{B}}$	$p'_{\text{sig } \ell}$
$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	$98.4 \pm 10.8$	$102.6 \pm 15.3$	$91.4 \pm 12.8$	$127.4 \pm 118.8$	$99.7 \pm 17.1$	-
$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	$136.1 \pm 11.8$	$146.1 \pm 16.0$	$137.2 \pm 13.3$	$192.4 \pm 48.8$	$79.3 \pm 50.2$	-
$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	$212.1 \pm 16.8$	$239.2 \pm 20.0$	$233.0 \pm 18.9$	$228.6 \pm 24.8$	$279.8 \pm 80.1$	-
$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	$62.4 \pm 9.0$	$57.7 \pm 11.4$	$59.2 \pm 8.8$	$52.8 \pm 11.7$	$64.7 \pm 14.0$	-
$B^+ \rightarrow \mu^+ \nu_\mu$	$11.5 \pm 5.0$	$13.9 \pm 5.8$	$15.1 \pm 9.9$	$11.5 \pm 7.3$	$14.8 \pm 19.1$	$12.7 \pm 7.6$
$B^+ \rightarrow e^+ \nu_e$	$14.6 \pm 5.3$	$13.6 \pm 8.5$	$24.0 \pm 11.2$	-	-	$35.0 \pm 17.8$

Use  $E_{\text{extra}}$  SB,  
cross Check  
with others



# Systematic Errors

$$\mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{N_{\text{obs}} - N_{\text{BG}}}{N_{BB} \varepsilon_{\text{tag}} \varepsilon_{\text{sig}}}$$

1.1%

Single Tag /  
Double Tag  
Studies

$E_{\text{extra}}$  shape in Double  
Tags

Tracking Efficiency

$\pi^0$  Selection

PID Corrections

Data/MC agreement  
from sidebands



# Tag Efficiency

$\varepsilon_1$  = tag efficiency

$\varepsilon_2$  = efficiency selected second tag

$$\varepsilon_1 \equiv \frac{N_{\text{single tags}}}{N_{B^+ B^-}}$$

$$\varepsilon_1 \times \varepsilon_2 \equiv \frac{N_{\text{double tags}}}{N_{B^+ B^-}} \Rightarrow \varepsilon_2 = \frac{N_{\text{double tags}}}{N_{B^+ B^-}} \cdot \frac{N_{B^+ B^-}}{N_{\text{single tags}}} = \frac{N_{\text{double tags}}}{N_{\text{single tags}}}$$

- Calculate  $\varepsilon_2$  for data and MC, take ratio as systematic correction to tag efficiency
- For all systematics, apply correction to MC and error on corr. as systematic error.



# Tag Efficiency

- For single tags, use one  $D^0$  decay mode, subtract  $D^0$  mass sidebands
- For double tags, use one tag  $D^0$  mode, all signal  $D^0$  modes, and no SB subtraction

Tag $D^0 \rightarrow K^- \pi^+$			
	Single Tags	Double Tags	$N_2/N_1$
Data	$812182.0 \pm 1132.4$	$2278.0 \pm 47.7$	$(0.280 \pm 0.006) \times 10^{-2}$
MC	$2611475.0 \pm 1945.4$	$8225.0 \pm 90.7$	$(0.315 \pm 0.003) \times 10^{-2}$
Data/MC	-	-	$0.891 \pm 0.021$

Tag $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$			
	Single Tags	Double Tags	$N_2/N_1$
Data	$602762.0 \pm 2034.0$	$2138.0 \pm 46.2$	$(0.355 \pm 0.008) \times 10^{-2}$
MC	$2051028.0 \pm 3468.0$	$8549.0 \pm 92.5$	$(0.417 \pm 0.005) \times 10^{-2}$
Data/MC	-	-	$0.851 \pm 0.021$

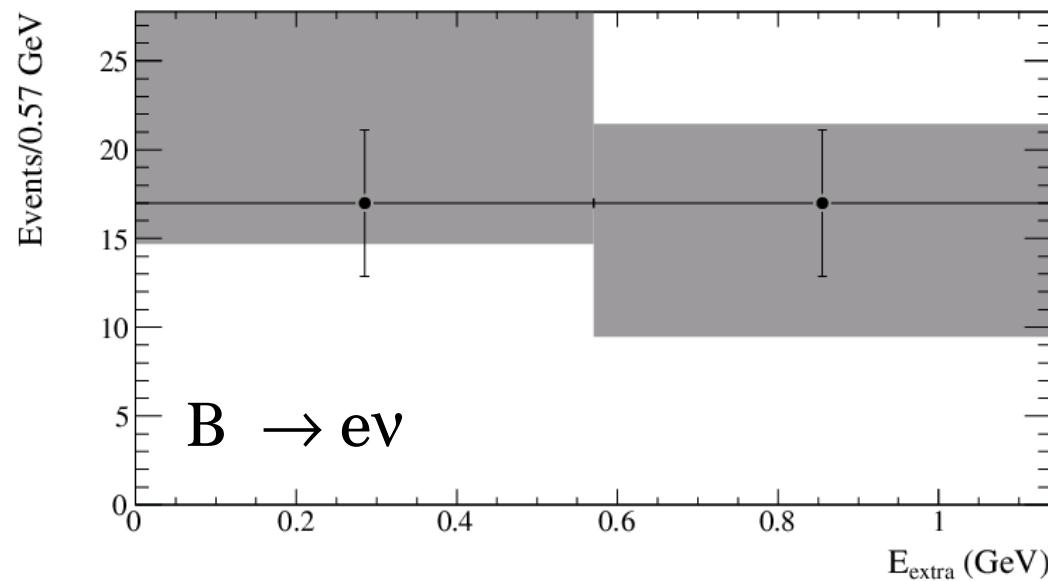


# Results $B \rightarrow e\nu$

Generic MC

• On Peak Data

— Signal MC



- ◆ Expected BG =  $24 \pm 11$ , Observed 17
- ◆ Set upper limit.

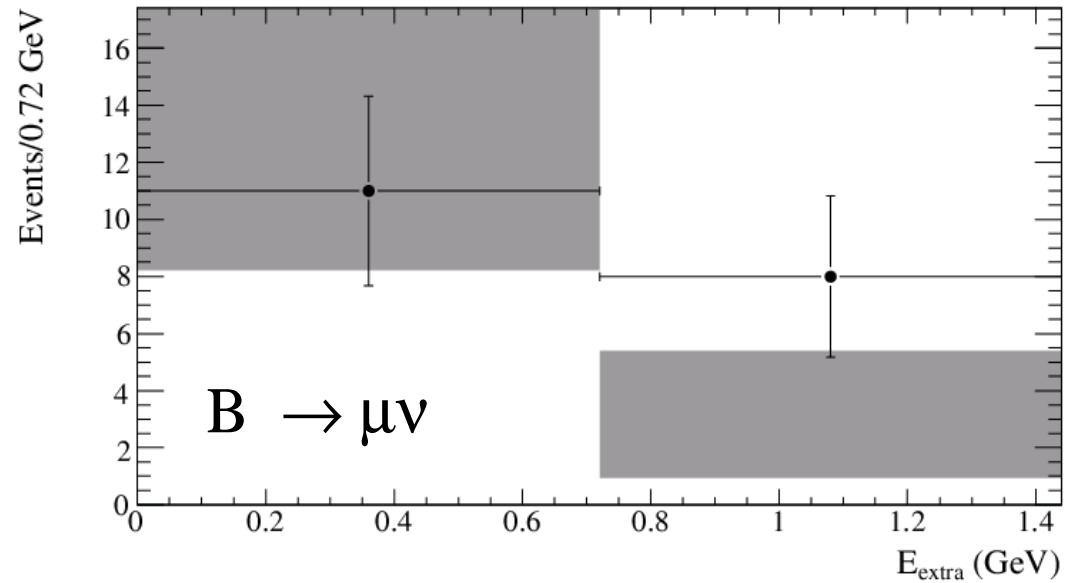


# Results $B \rightarrow \mu\nu$

Generic MC

• On Peak Data

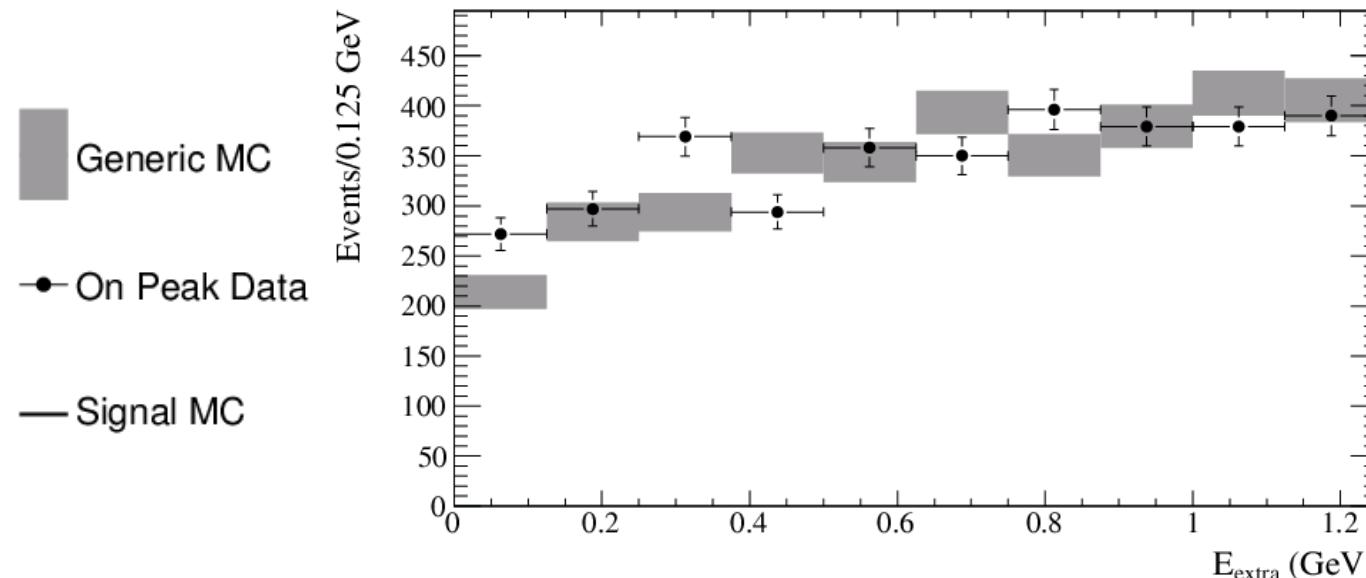
— Signal MC



- ◆ Expected BG =  $15 \pm 10$ , Observed 11
- ◆ Set upper limit.



# Results $B \rightarrow \tau\nu$



- Total Expected BG  $521 \pm 31$
- Observed 610
- Measure branching fraction.

Mode	Expected Background ( $N_{\text{BG}}$ )	Observed Events ( $N_{\text{obs}}$ )
$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	$91 \pm 13$	148
$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	$137 \pm 13$	148
$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	$233 \pm 19$	243
$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	$59 \pm 9$	71

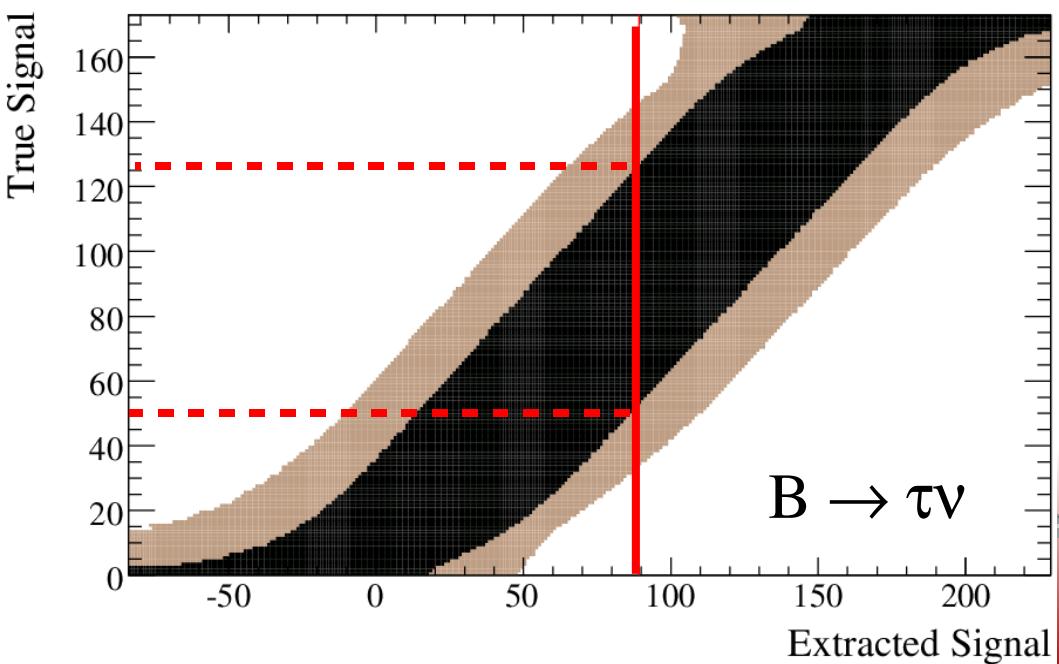
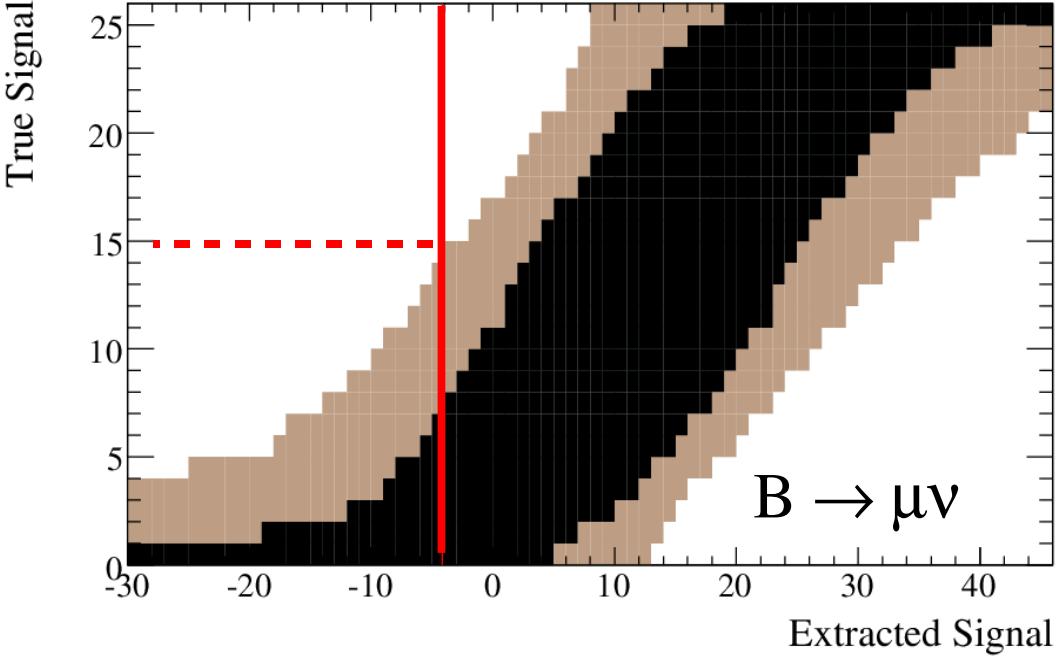
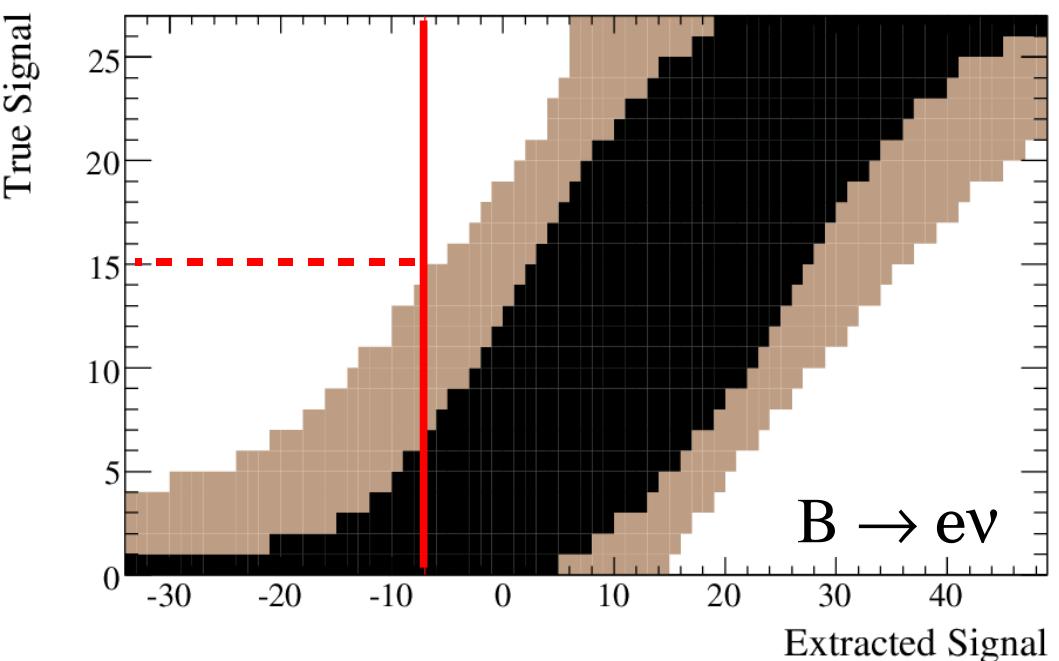


# Feldman-Cousins

- How do we convert raw numbers in branching fractions and upper limits?
- We choose Feldman-Cousins method
  - ◆ *Phys. Rev. D*57:3873-3889
- Uses MC to set branching fraction or upper limit
- Works in high and low background environments



# CL Histograms

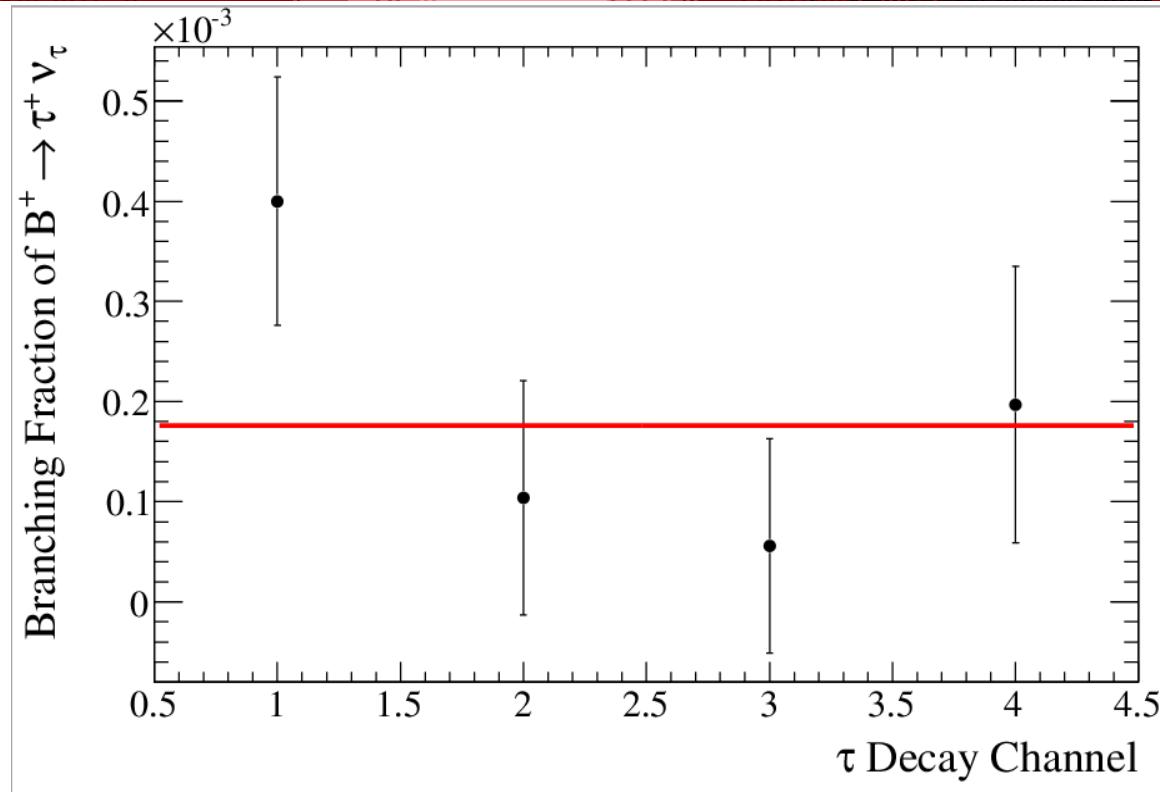


- ◆ Red line is unblinded value
- ◆ Central Band =  $1\sigma$
- ◆ Outer Band is 90% CL



# Agreement of Branching Fractions

- Fit histogram of separate BFs
- Fit to constant -> probability of 18%



Mode	Expected Background ( $N_{BG}$ )	Observed Events ( $N_{obs}$ )	Overall Efficiency ( $\varepsilon$ )	Branching Fraction
1 $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	$91 \pm 13$	148	$(3.08 \pm 0.14) \times 10^{-4}$	$(4.0 \pm 1.2) \times 10^{-4}$
2 $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	$137 \pm 13$	148	$(2.28 \pm 0.11) \times 10^{-4}$	$\left(1.0^{+1.2}_{-0.9}\right) \times 10^{-4}$
3 $\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	$233 \pm 19$	243	$(3.89 \pm 0.15) \times 10^{-4}$	$\left(0.6^{+1.1}_{-0.5}\right) \times 10^{-4}$
4 $\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	$59 \pm 9$	71	$(1.30 \pm 0.07) \times 10^{-4}$	$\left(2.0^{+1.4}_{-1.3}\right) \times 10^{-4}$

# Results

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = (1.8 \pm 0.8 \pm 0.1) \times 10^{-4} (2.4 \sigma)$$

$$f_B = 255 \pm 58 \text{ MeV}$$

$$\mathcal{B}(B^+ \rightarrow \mu^+ \nu) < 11 \times 10^{-6} @ 90\% \text{ CL}$$

$$\mathcal{B}(B^+ \rightarrow e^+ \nu) < 7.7 \times 10^{-6} @ 90\% \text{ CL}$$

Combined with hadronic tag (*Phys. Rev.* **D77**:011107)

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = (1.8 \pm 0.6) \times 10^{-4} (3.2 \sigma)$$



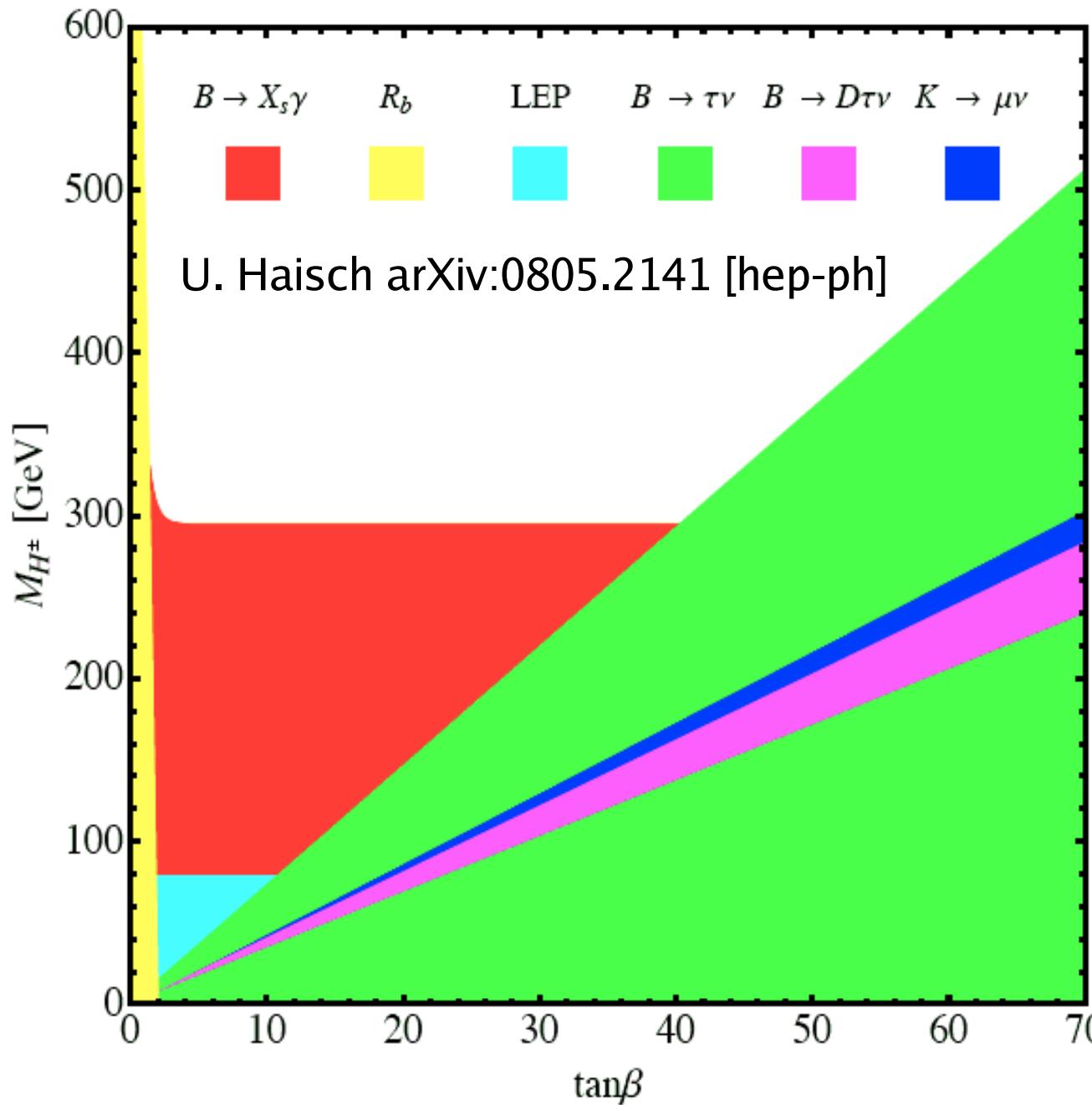
# Context

		$B^+ \rightarrow e^+ \nu_e$	$B^+ \rightarrow \mu^+ \nu_\mu$	$B^+ \rightarrow \tau^+ \nu_\tau$
PDG Values [1]		$< 9.8 \times 10^{-7}$	$< 1.7 \times 10^{-6}$	$(1.4 \pm 0.4) \times 10^{-4}$
Inclusive Meas.	<i>BABAR</i> [9]	-	$< 1.3 \times 10^{-6}$	N/A
	<i>Belle</i> [10]	$< 9.8 \times 10^{-7}$	$< 1.7 \times 10^{-6}$	N/A
Hadronic Tag Meas.	<i>BABAR</i>	$< 5.2 \times 10^{-6}$ [11]	$< 5.6 \times 10^{-6}$ [11]	$(1.8_{-0.9}^{+1.0}) \times 10^{-4}$ [12]
	<i>Belle</i>	-	-	$(1.8 \pm 0.7) \times 10^{-4}$ [13]
Semilep. Tag Meas.	<i>BABAR</i>	$< 7.7 \times 10^{-6}$	$< 11 \times 10^{-6}$	$(1.8 \pm 0.8 \pm 0.1) \times 10^{-4}$
	<i>Belle</i> [14]	-	-	$(1.65_{-0.37-0.37}^{+0.38+0.35}) \times 10^{-4}$

- ◆  $B \rightarrow \tau v$ : consistent with all recent measurements
- ◆  $B \rightarrow \mu v$ : 11 events in sig. region (Inclusive: 600)
  - ◆ Smaller backgrounds are more conducive to discovery
  - ◆ Precision measurement at Super B factory



# New Physics from $B \rightarrow \tau\nu$ ?



- Shaded regions are excluded at 95% CL



# Future Outlook



- ♦ Publish this work
- ♦ Combined tags and Belle + Babar
  - ♦  $B \rightarrow \tau v$  @  $5\sigma$
  - ♦  $B \rightarrow uv$  first evidence
- ♦ Super B precision measurements.



# Backup Slides



# Predictions before mll cut

## Signal Predictions

Mode	Prediction
$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	$15.42 \pm 0.33$
$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	$12.09 \pm 0.29$
$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	$18.96 \pm 0.37$
$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	$6.56 \pm 0.22$
$B^+ \rightarrow \tau^+ \nu_\tau$	$53.03 \pm 0.63$
$B^+ \rightarrow \mu^+ \nu_\mu$	$0.74 \pm 0.01$
$B^+ \rightarrow e^+ \nu_e$	$(1.84 \pm 0.02) \times 10^{-5}$

## Signal Predictions Assuming

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = 1.0 \times 10^{-4}$$

$$\mathcal{B}(B^+ \rightarrow \mu^+ \nu) = 5.0 \times 10^{-7}$$

$$\mathcal{B}(B^+ \rightarrow e^+ \nu) = 1.0 \times 10^{-11}$$

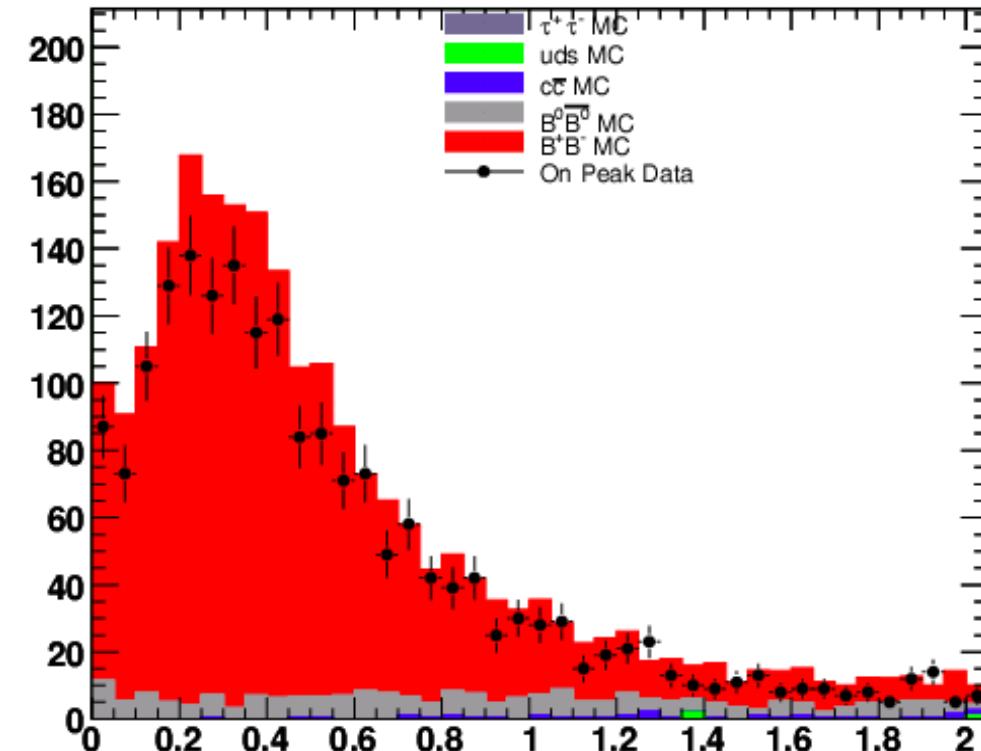
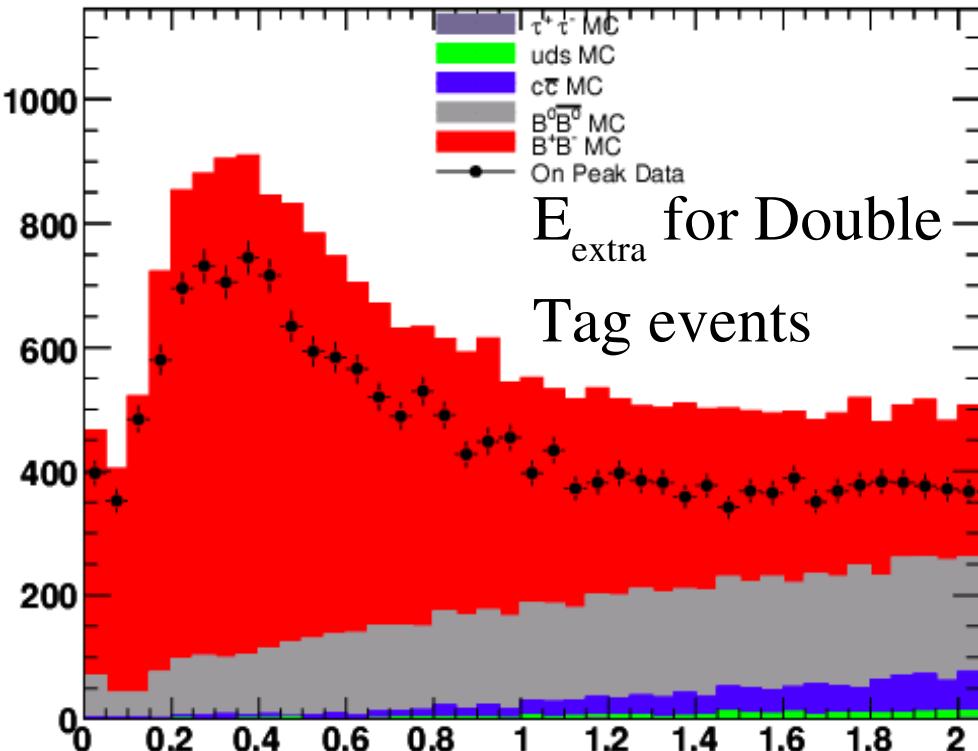
- We do not use  $\tau \rightarrow \pi\pi\pi$  mode because it lowers significance

Table 83: Comparison of BG predictions from various sidebands.

Mode	MC Counting	$D^0$ Mass	$E_{\text{extra}}$	$LHR_{\text{cont.}}$	$LHR_{B\bar{B}}$	$p'_{\text{sig } \ell}$
$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	$109.8 \pm 12.0$	$123.8 \pm 17.7$	$104.5 \pm 14.3$	$198.9 \pm 112.4$	$110.3 \pm 18.9$	-
$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	$136.1 \pm 11.8$	$146.1 \pm 16.0$	$137.2 \pm 13.3$	$192.4 \pm 48.8$	$79.3 \pm 50.2$	-
$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	$212.1 \pm 16.8$	$239.2 \pm 20.0$	$233.0 \pm 18.9$	$228.6 \pm 24.8$	$279.8 \pm 80.1$	-
$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	$62.4 \pm 9.0$	$57.7 \pm 11.4$	$59.2 \pm 8.8$	$52.8 \pm 11.7$	$64.7 \pm 14.0$	-
$\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$	$122.9 \pm 12.2$	$119.8 \pm 17.3$	$121.7 \pm 12.6$	$116.6 \pm 16.2$	$127.0 \pm 14.0$	-
$B^+ \rightarrow \mu^+ \nu_\mu$	$11.5 \pm 5.0$	$13.9 \pm 5.8$	$15.1 \pm 9.9$	$11.5 \pm 7.3$	$14.8 \pm 19.1$	$12.7 \pm 7.6$
$B^+ \rightarrow e^+ \nu_e$	$14.6 \pm 5.3$	$13.6 \pm 8.5$	$24.0 \pm 11.2$	-	-	$35.0 \pm 17.8$



# $E_{\text{extra}}$ in Double Tags

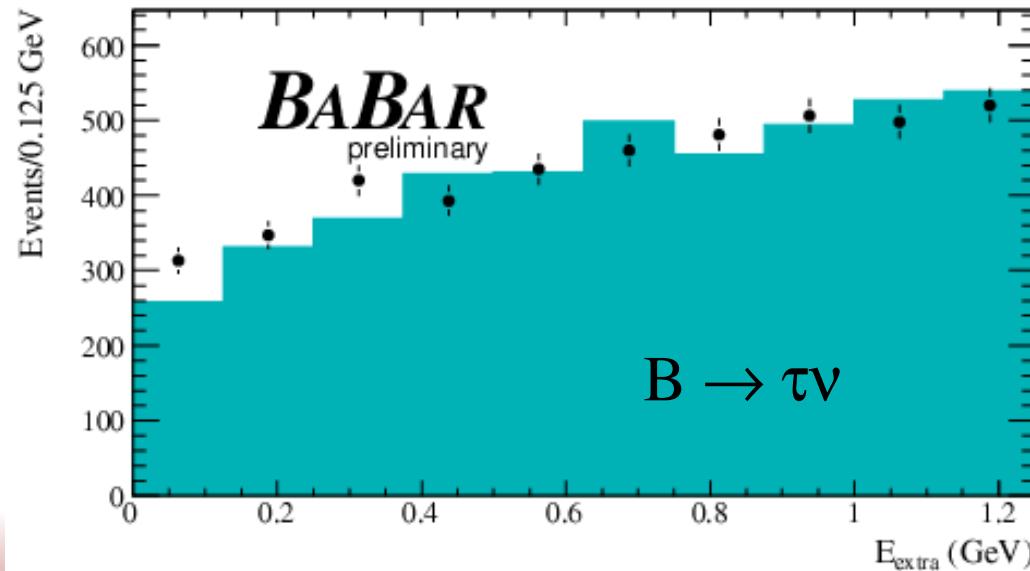
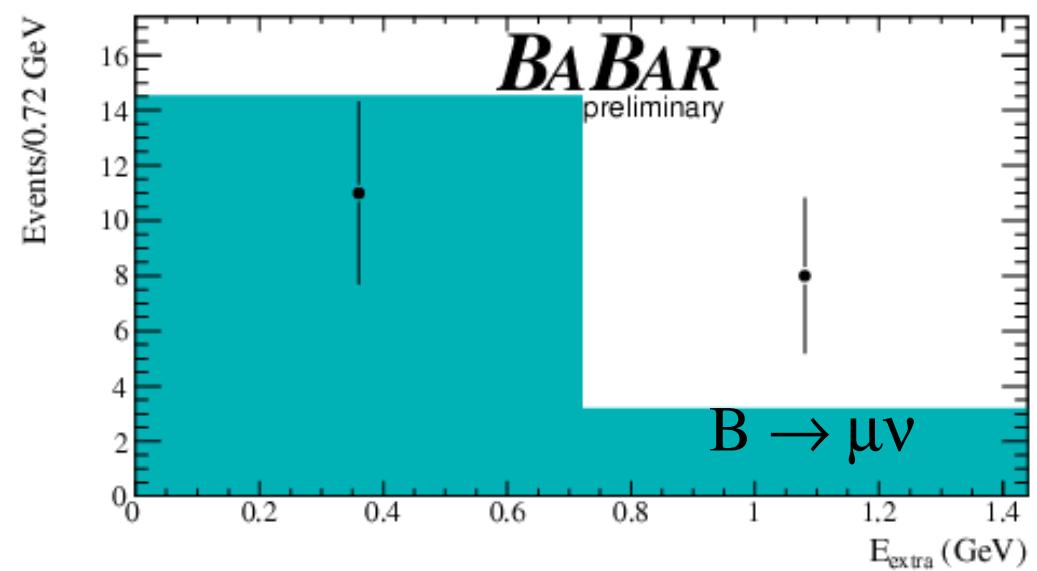
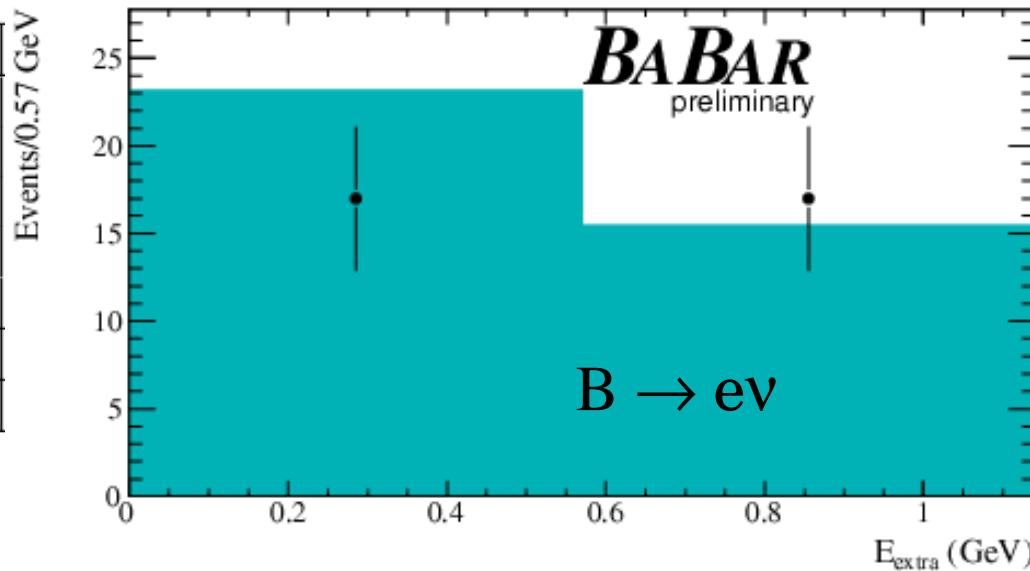


- Left: same cuts on second tag as on first
- Right: Add cut  $-2.0 < \text{CosBY} < 1.1$  Net Charge = 0



# Unblinded Results before

Mode	Expected Background	Observed Events
$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	$104.5 \pm 14.3$	170
$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	$137.2 \pm 13.3$	148
$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	$233.0 \pm 18.9$	243
$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	$59.2 \pm 8.8$	71
$B^+ \rightarrow \tau^+ \nu_\tau$	$533.9 \pm 31.3$	632
$B^+ \rightarrow \mu^+ \nu_\mu$	$15.2 \pm 9.9$	11
$B^+ \rightarrow e^+ \nu_e$	$24.0 \pm 11.2$	17



- ◆ Only applies for
- ◆ Assume that most of our  $\pi^0$  candidates are not merged
- ◆ According to Wolfgang Gradl, we should use the same correction and error as in R18
- ◆  $0.984 \pm 0.030$



## ◆ Tracking Eff.

- ◆ No correction, Overall uncertainty of 0.27%
- ◆ Additional uncertainty of 0.23% per track
- ◆ Total 0.69% for  $\tau \rightarrow \pi\pi\pi$ , 0.36% for all others

## ◆ Particle ID

- ◆ Time constraints prevented full study before ICHEP deadlines
- ◆ Use systematics from previous analysis (BAD 1456)



# Solution 2

- Frank Porter pointed out that I was underestimating error in Feldman Cousins
- Two sources of error
  - ◆ Error in the background prediction
  - ◆ Stat. error in the number of observed events ( $N_{\text{obs}}$ )
- In FC method, toy MC (random numbers) are used to estimate the probability the probability of various measurements.



# Conclusions I

- Use Feldman-Cousins Method

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = (2.0 \pm 0.6 \pm 0.1) \times 10^{-4}$$

- Belle (Hadronic Tag):  $(1.8 \pm 0.7) \times 10^{-4}$  (PDG)

Belle  
Hadronic

- Babar Hadronic  $(1.8^{+1.0}_{-0.9}) \times 10^{-4}$

- PRD 77:011107, 2008

$$f_B = 240 \pm 48 \pm 4 \text{ MeV}$$

- Using  $|V_{ub}| = (4.39 \pm 0.54) \times 10^{-3}$

- Compare Belle  $f_B = 229^{+36+34}_{-31-37} \text{ MeV}$  (PRL 97:251802, 2006)



# Conclusions II



- ◆ Babar Inclusive:  $< 1.3 \times 10^{-6}$ 
  - ◆ Elisabetta Baracchini (BAD 1956)
- ◆ This work: 11 events in sig. region (Inclusive: 600)
- ◆  $\mathcal{B}(B^+ \rightarrow e^+ \nu) < 6.9 \times 10^{-6} @ 90\% \text{ CL}$
- ◆ Belle Inclusive:  $< 9.8 \times 10^{-7}$  (PDG)
- ◆ Smaller backgrounds are more conducive to discovery



# Problem Found

Mode	Expected Background	Observed Events	FOM
$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	$104.5 \pm 14.3$	170	5.03
$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	$137.2 \pm 13.3$	148	0.89
$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	$233.0 \pm 18.9$	243	0.64
$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	$59.2 \pm 8.8$	71	1.4
$B^+ \rightarrow \tau^+ \nu_\tau$	$533.9 \pm 31.3$	632	3.9
$B^+ \rightarrow \mu^+ \nu_\mu$	$15.2 \pm 9.9$	11	-2.77
$B^+ \rightarrow e^+ \nu_e$	$24.0 \pm 11.2$	17	-4.67

Problem: Large excess found only in  $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$

Re-examine potential background sources.

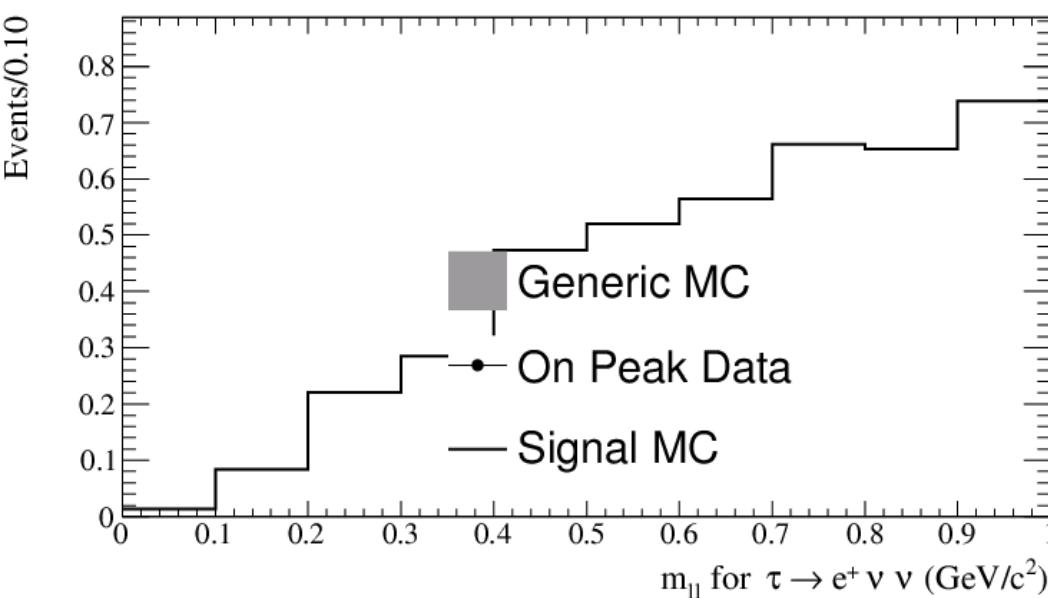
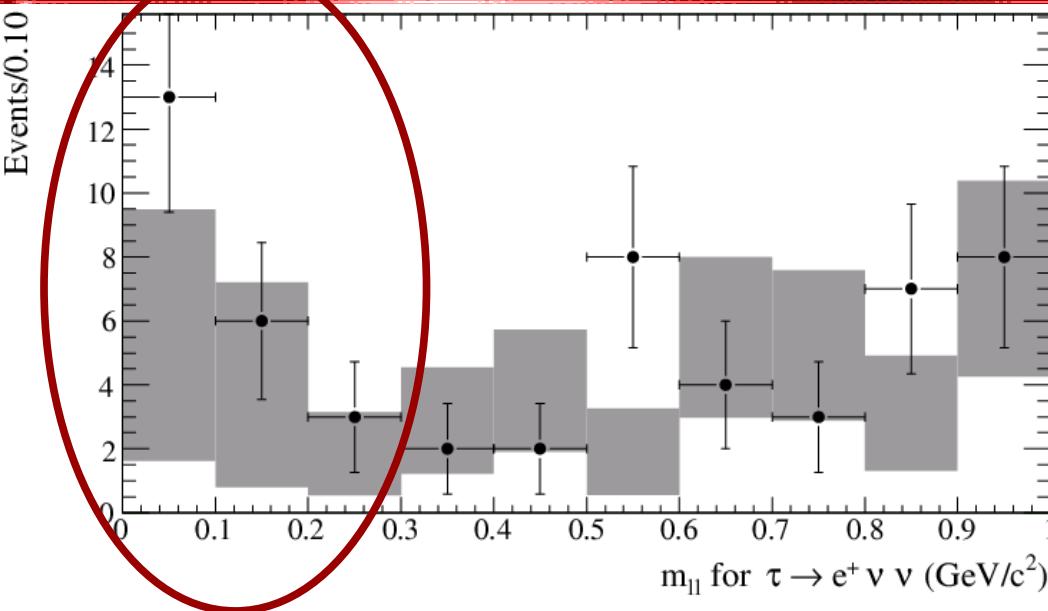


# Potential Background Sources

- ◆ Two photon fusion QED events
- ◆ “Events” with two overlapping  $e^+e^-$  collisions
- ◆ Overzealous Bremsstrahlung recovery
- ◆ Photon pair production
  - ◆  $e^+, e^-$  reconstructed as the tag and signal lepton
  - ◆ One lepton is lost, and the other reconstructed as the signal electron.



# One source found



- ◆ Photon pair production:  $e^+$ ,  $e^-$  reconstructed as the tag and signal lepton
- ◆ Found in invariant mass of two leptons  $m_{ll}$
- ◆ Other sources shown to not contribute



# Solution

- $m_{ll}$  included in a PDF, but this was not sufficiently effective
- After all cuts have been made, optimize  $m_{ll}$  cut separately
- No data used in optimization, only generic and signal MC.
- Optimizer returns  $m_{ll} > 0.29 \text{ GeV}$



# Feldman-Cousins

For each value  $N_{\text{true}}$ , order values of  $N_{\text{sig}}$  by  $R$

$$= P(N_{\text{sig}} | N_{\text{true}}) / P(N_{\text{sig}} | N_{\text{best}})$$

$N_{\text{best}}$  is the value of  $N_{\text{true}}$  that maximizes the probability of observing  $N_{\text{sig}}$  (usually  $N_{\text{true}}$ )

Sum probabilities until one reaches desired confidence level.

For unblinded data  $N_{\text{sig}} = N_{\text{obs}} - N_{\text{BG}}$



# Summary of Systematics

Source	Applicable Mode(s)	Correction	Fractional Uncertainty (%)
$B$ Counting	All	1.0	1.1
Tag efficiency	All	$0.891 \pm 0.021$	2.4
$E_{\text{extra}}$	All	$1.015 \pm 0.021$	2.1
$\pi^0$ Reconstruction	$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	$0.984 \pm 0.030$	3.0
Tracking Efficiency	$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	1.0	0.36
	$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	1.0	0.36
	$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	1.0	0.36
	$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	1.0	0.36
	$\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$	1.0	0.74
	$B^+ \rightarrow \mu^+ \nu_\mu$	1.0	0.36
	$B^+ \rightarrow e^+ \nu_e$	1.0	0.36
Particle Identification	$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	1.01	2.5
	$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	0.92	3.1
	$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	1.02	0.8
	$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	1.00	1.5
	$\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$	1.06	2.4
	$B^+ \rightarrow \mu^+ \nu_\mu$	0.92	3.1
	$B^+ \rightarrow e^+ \nu_e$	1.01	2.5



# Signal Reconstruction

- ♦ After tag is reconstructed, search remainder of event.
- ♦ Events are assigned to different signal categories in a hierarchy based on mass, PID and other requirements

Decay Mode	Branching Ratio
$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	( 17.84 $\pm$ 0.05 ) %
$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	( 17.36 $\pm$ 0.05 ) %
$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	( 10.90 $\pm$ 0.07 ) %
$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	( 25.50 $\pm$ 0.10 ) %
$\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$	( 9.33 $\pm$ 0.08 ) %



# Predictions

## Signal Predictions

Mode	Signal Prediction
$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	$15.14 \pm 0.33$
$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	$12.09 \pm 0.29$
$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	$18.96 \pm 0.37$
$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	$6.56 \pm 0.22$
$B^+ \rightarrow \tau^+ \nu_\tau$	$53.03 \pm 0.63$
$B^+ \rightarrow \mu^+ \nu_\mu$	$0.74 \pm 0.01$
$B^+ \rightarrow e^+ \nu_e$	$(1.84 \pm 0.02) \times 10^{-5}$

## Signal Predictions Assuming

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = 1.0 \times 10^{-4}$$

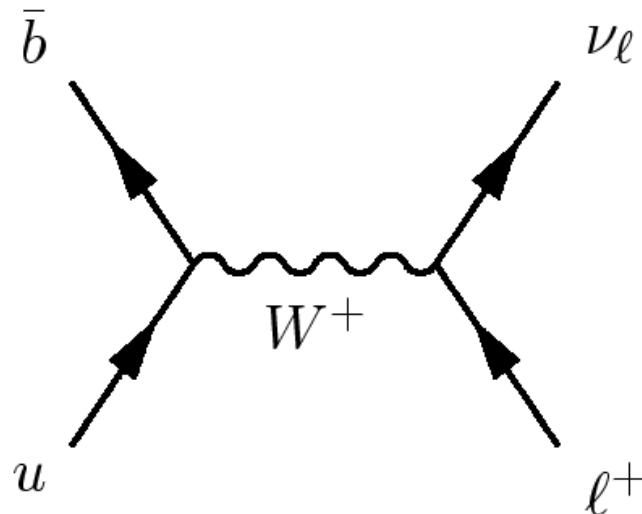
$$\mathcal{B}(B^+ \rightarrow \mu^+ \nu) = 5.0 \times 10^{-7}$$

$$\mathcal{B}(B^+ \rightarrow e^+ \nu) = 1.0 \times 10^{-11}$$

Mode	MC Counting	$D^0$ Mass	$E_{\text{extra}}$	$LHR_{\text{cont.}}$	$LHR_{B\bar{B}}$	$p'_{\text{sig } \ell}$
$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	$98.4 \pm 10.8$	$102.6 \pm 15.3$	$91.4 \pm 12.8$	$127.4 \pm 118.8$	$99.7 \pm 17.1$	-
$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	$136.1 \pm 11.8$	$146.1 \pm 16.0$	$137.2 \pm 13.3$	$192.4 \pm 48.8$	$79.3 \pm 50.2$	-
$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	$212.1 \pm 16.8$	$239.2 \pm 20.0$	$233.0 \pm 18.9$	$228.6 \pm 24.8$	$279.8 \pm 80.1$	-
$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$	$62.4 \pm 9.0$	$57.7 \pm 11.4$	$59.2 \pm 8.8$	$52.8 \pm 11.7$	$64.7 \pm 14.0$	-
$\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$	$122.9 \pm 12.2$	$119.8 \pm 17.3$	$121.7 \pm 12.6$	$116.6 \pm 16.2$	$127.0 \pm 14.0$	-
$B^+ \rightarrow \mu^+ \nu_\mu$	$11.5 \pm 5.0$	$13.9 \pm 5.8$	$15.1 \pm 9.9$	$11.5 \pm 7.3$	$14.8 \pm 19.1$	$12.7 \pm 7.6$
$B^+ \rightarrow e^+ \nu_e$	$14.6 \pm 5.3$	$13.6 \pm 8.5$	$24.0 \pm 11.2$	-	-	$35.0 \pm 17.8$



# Standard Model Predictions



$$\mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

Calculate from branching fraction

Helicity suppresses the BFs of the light leptons

SM Prediction

$$|V_{ub}| = (4.39 \pm 0.54) \times 10^{-3} \text{ [3]}, f_B = 0.189 \pm 0.027 \text{ GeV [8]}$$

		$B^+ \rightarrow e^+ \nu_e$	$B^+ \rightarrow \mu^+ \nu_\mu$	$B^+ \rightarrow \tau^+ \nu_\tau$
Prediction	Naive SM	$(1.3 \pm 0.4) \times 10^{-11}$	$(5.6 \pm 1.7) \times 10^{-7}$	$(1.2 \pm 0.4) \times 10^{-4}$
	CKM Fitter [8]	$0.89^{+0.12}_{-0.09} \times 10^{-11}$	$(3.8^{+0.5}_{-0.4}) \times 10^{-7}$	$(0.93^{+0.12}_{-0.09}) \times 10^{-4}$
	UT Fitter [7]	-	-	$(0.86 \pm 0.16) \times 10^{-4}$
PDG Values [1]		$< 9.8 \times 10^{-7}$	$< 1.7 \times 10^{-6}$	$(1.4 \pm 0.4) \times 10^{-4}$

[3] B. Aubert, *et al.* PRL, 96:221801 (2006) [8] <http://ckmfitter.in2p3.fr> [1] PDG 2008

[7] <http://utfit.roma1.infn.it/btaunu/ckm-btaunu.html>

# Signal Eff. systematics

Optimized cuts on all variables except  $E_{\text{extra}}$

Take (# events in signal region/# of total events) for Data and MC.

Ratio of Data/MC gives the systematic correction and error on modeling of  $E_{\text{extra}}$

Result  $1.015 \pm 0.021$



# $\pi^0$ Selection, Tracking Eff., PID

For  $\tau^+ \rightarrow \rho^+ \nu$  ( $\rho^+ \rightarrow \pi^+ \pi^0$ ) error:  $0.984 \pm 0.030$

Tracking Eff.

No correction, Overall uncertainty of 0.27%

Additional uncertainty of 0.23% per track

Particle ID

Few differences with previous analysis

*Phys. Rev. D76:052002*

Use same systematics in this one



# Feldman-Cousins

Create 2D histogram of  $N_{\text{true}}$  (generated)  
signal vs. extracted signal

100,000 experiments per true value

Extracted signal = total entries – BG prediction

Smooth statistical variations by fitting each  
horizontal strip to sum of two Gaussians



# First Histogram $B \rightarrow \mu\nu$

